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Theoretical Considerations from Chinese Practices

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Preface

Construction Management: Chinese Scholars' Repeating Narration to Subsequent Narration

Although it took approximately 3 years for my writing to finally culminate in this book, I spent nearly 30 years thinking through related problems to form and streamline a relatively complete system.

The main reasons for investing so much time in writing about the fundamental theory of mega infrastructure construction management are as follows:

1. This book contains numerous new academic ideas and theoretical opinions that require lengthy consideration.
2. Though many of the investigated concepts and theories are independent, they are correlated. The entire theoretical system, which includes fundamental concepts, theories, scientific problems, and methodologies, must be systematic and logical, which requires considerable time and effort to create.
3. The discussed theoretical contents require the guidance and support of construction management practice activities. Accordingly, germination and growth are lengthy processes in producing and achieving the theoretical formation threshold.
4. The content herein fully demonstrates the combination and integration of multiple disciplines, and it also requires the gradual development of an interdisciplinary academic environment.

Therefore, the writing and publishing efforts not only record the long academic research path of the writer but also reflect the explorative process of Chinese scholars and construction practitioners of mega infrastructure construction management theories.

One

Many years ago, Chongqing Guo, a famous Chinese management scientist and academician, argued that to facilitate further development, Chinese management science ought to transition gradually from the Repeating Narration stage, which relies heavily on foreign academic thought, to the Subsequent Narration stage, which is practice oriented and focuses on the innovation of management theory. This is not only the purpose of Chinese management scholars but also the historical responsibility of Chinese construction management scholars.

Thirty years ago, due to little historical heritage and the short development period of construction management in China, Chinese scholars focused primarily on the introduction and adaptation of foreign construction management knowledge systems and methods centered on project management. Endeavoring to apply the knowledge and methods to Chinese construction management practices during those initial growth periods was necessary and important for construction and management in China. The foreign project management system plays an important role in the development and progress of Chinese construction management. It is, and will continue to be, a crucial element. In general, work related to Chinese construction management during this period belonged to the Repeating Narration period, which relied on the foreign construction management knowledge system.

However, this 30-year period experienced the fastest development of construction engineering in the world, especially in China. In addition, the construction management field realized great advancements and development. With the constant expansion of Chinese construction engineering, infrastructure construction has become an essential part of the social and economic development of China.

On the one hand, massive practical problems in construction management not only require the use of the direct application of foreign construction management knowledge and methods but also must be considered according to the actual situation of Chinese construction management when developing new construction management ideas and theories. On the other hand, constantly enriching practices of Chinese construction management together with massive practical management experiences provides fertile soil for the consideration and creation of theories.

To put it simply, the evolution of current construction management in China has reached an important turning point. The crucial task is to change from the Repeating Narration period, where foreign construction management (primarily project management) knowledge and methods are purely introduced and absorbed, to a new period that further summarizes the management experience and refines the theoretical elements to form a new construction management theory based on construction management practices. Thus, the new Subsequent Narration period of Chinese construction management would most certainly involve unique construction management problems related to the Chinese environment and culture, as well as focus on theoretical construction management problems, which would be sourced from construction practices in China but could be applied universally and extended for tremendous fundamental significance. For example, some construction management problems arise in construction practices both at home and abroad. Subsequent Narration would reveal and theoretically explain new and in-depth laws. Furthermore, new problems of universal value exist in foreign construction practices in China, without being conspicuously obvious. Subsequent Narration would explore these problems theoretically not by focusing on experiences limited to the national situation and cultural features of China or common skills and operating techniques in practical construction management activities but by focusing instead on the theoretical innovation of construction management.

Repeating Narration and Subsequent Narration, though both are forms of narration, are vastly different. Repeating Narration discusses knowledge and methods of foreign construction management, while Subsequent Narration focuses more on the research of construction management practices in China and the refinement of the universal scientific theory based on these Chinese practices.

Two

Engineering management in China has a solid foundation of practice and theoretical preparation, transitioning from Repeating Narration to Subsequent Narration.

Over the past 30 years, China has become the world's leading construction country, not only through maintained large-scale construction projects but also due to many major emerging world-renowned projects. The number and size of major projects already built or currently in progress in China rank first in the world, thus providing a rich, deep, direct source to examine major construction management theory and serving as the most valuable practical resource in the field of construction management in China.

Through diverse engineering functions, major projects are divided into scientific and technological, military defense, and infrastructure construction. Among these, infrastructure construction not only encompasses a wide range of work but also fully reflects basic project characteristics and basic features of economics, management, and other scientific systems. Therefore, from the perspective of the significance of the mega infrastructure construction management science system, the conducting of research on management theory of mega infrastructure construction is of universal significance. As the focal point of this study, mega infrastructure construction refers specifically to mega infrastructure projects, such as large-scale hydraulic engineering, major environmental engineering, and large bridge, tunnel, and other major transportation hub construction. Mega infrastructure construction management theory is interdisciplinary and comprehensive, involving many fields, including natural sciences, engineering sciences, technical sciences, social sciences, and humanities. Subsequent Narration requires not only the integrated use of these sciences but also the methodological guidance of philosophical wisdom and cultural connotations. Chinese philosophical comprehensive thinking and integrated, wise cultural thought contribute to the thinking principle and thinking route of the

Chinese engineering management scholars' mega infrastructure construction management theory, i.e., Subsequent Narration.

Though Chinese construction management scholars have used Repeating Narration over the years, at the same time, they have continued to explore Subsequent Narration. Combining the accumulated experience with the formation of new theoretical elements, the necessary preparations are in place to further this mega infrastructure construction management theory.

Based on the aforementioned points, Subsequent Narration requires Chinese scholars to utilize a variety of practical resource advantages while focusing on the innovation of the mega infrastructure construction management theory.

Thus, Chinese scholars have transformed construction management from Repeating Narration to Subsequent Narration, the latter of which is based on abundant mega infrastructure construction management practices and requires the guidance of scientific philosophical thinking. Moreover, both of these aspects must be closely combined. Specifically, with the continual expansion of the academic turning point regarding Chinese mega infrastructure construction management practices and the increasing demand for theoretical innovation, the project management knowledge system, which relies on emphasizing Chinese traditional cultural wisdom, and the proposed academic self-assertion and autonomy based on complex holism are necessary to achieve a new Subsequent Narration of mega infrastructure construction management. In this way, the transition from Repeating Narration to the new process of Subsequent Narration is manifested. This scenario indicates that Subsequent Narration for construction management is theoretically significant and has innovation value. Therefore, we do not follow the traditional project management system path, nor do we discuss only several new phenomena and fragmented field problems of mega infrastructure construction management. Rather, we consider that we should discuss the mega infrastructure construction theoretical system of academic self-assertion with distinct systematicness and clear organization, including basic principles, concepts, theories, issues, and methods as well as the integrated academic discourse system based on these assertions.

According to the concept of basic theory in science philosophy, mega infrastructure construction management basic theory refers to the research of mega infrastructure construction management activities with respect to general or primary laws in the theoretical system and the theoretical basis guiding the significance of practical management activities. This theory incorporates the basic fundamental and universal theoretical principles and original philosophy in mega infrastructure construction management systems. A more detailed explanation of this management theory is as follows:

1. The basic ideas and behavior principles of the management body in the mega infrastructure construction management activities.
2. The basic patterns and principles of the management body's thinking and behavior through the mega infrastructure construction management activities.
3. The principles and the basic form of the mega infrastructure construction management activities are comprehensively established by the management body based on environmental management, management objectives, and management issues.

Thus, given the above details, Chinese scholars should highlight the important theoretical aspects of mega infrastructure construction management in the Subsequent Narration stage of construction management.

The establishment of this principle embodies the true meaning and value of Chinese scholars' Subsequent Narration theory, as well as Chinese mega infrastructure construction management practice and innovation. Although Chinese construction management scholars transformed Repeating Narration into Subsequent Narration, this does not mean that the foreign project management system will be replaced or that its existence will be denied. The development of the critical role of the construction management system by Chinese scholars involves systematic thinking about the mega infrastructure construction management theory. At the same time, it involves typical practices as part of the academic growth of China's construction management. Moreover, by developing the project management system and its connotation, China's construction management theory reflects the Chinese culture and philosophy as well as the realistic and legitimate vitality produced from what Hegel called the East–West cultural integration. Therefore, this book embodies the theoretical exploration and thinking of Chinese scholars in the field of construction management at the Subsequent Narration stage.

To do so, the following principles must be acknowledged:

1. The principles, with respect to mega infrastructure construction, must remain rooted in management practice. As construction management is a practical science, if the summary of mega infrastructure construction management rules and management theory departs from the practice of construction management, its persuasive, explanatory, analytical, and predictive power, as well as the level of control, cannot be guaranteed.
2. Innovated theoretical research must be mandated. Subsequent Narration is an academic innovation behavior. Theoretical research cannot just examine the general interpretations and annotations of the existing knowledge and experience, as doing so would minimize the academic value of such research.
3. The unity of Subsequent Narration and Repeating Narration must be maintained, as Repeating Narration is not excluded from Subsequent Narration in construction management. Regardless of the research or innovation under investigation, the study itself and the comprehensive understanding of the information and ideas are always prerequisites to the improvement and development of construction management. In other words, for Subsequent Narration to prosper and succeed, Repeating Narration must occur first. This concept is consistent with the premise that any scientific civilization has always developed from learning and inheritance.

Three

In conclusion, Subsequent Narration should narrate how to conduct theoretical research and implement innovation based on mega infrastructure construction management practices in China. Accordingly, the first step must be to establish theoretical thinking principles and form a theoretical system that clearly defines the theoretical research objectives, the nature of mega infrastructure construction, and mega infrastructure construction management.

As Einstein said, “If the scope and general concepts are not defined, thinking is like breathing in a vacuum; it is impossible.” In this regard, this book combines the Subsequent Narration of construction management scholars in China with traditional Chinese philosophy, contemporary integrated system theory, and an international comprehensive system of science to form a new and complex integral cognition about mega infrastructure construction management by establishing a path of thinking about mega infrastructure construction management theory.

Because of their different levels, all theoretical issues of mega infrastructure construction management are clearly and completely discussed. Therefore, to stress the key point, problems, whether simple or complex, do not need to be narrated. Rather, issues that fully reflect the essential characteristics of mega infrastructure construction management and research of new phenomena related to the theoretical thinking category should be the focus of the study.

More specifically, this book, based on the important academic philosophy that “The construction is the body, the system is the soul,” finds that the main objective of mega infrastructure construction management theory research is to resolve a class of issues relevant to and evident in the management activity that causes management to reflect characteristics of unclear structure, unknown mechanisms, and strong dynamics with substantial environmental influence. These issues include a lack of sufficient resources, the absence of recognition, and the inability to control management activities. Consequently, these issues cannot be solved by using traditional experience and existing methods. Rather, they require new and innovative thinking and the integration of more resources to build a new platform and form new capabilities.

For example, mega infrastructure construction project planning, decision authentication, construction design, construction organization models, mega construction schemes, investment and financing practices, technical management, integrated field control, and construction risk management belong to this class of issues. However, this class of management issues possesses complex integrity, which cannot be resolved, and achieves little success from general construction management technology or system construction methods. Therefore, new complex management methods must be used to resolve these issues.

Although this class of issues generally appears at the macro and strategic levels of mega infrastructure construction management and may not constitute a particularly substantial percentage of total management issues, their complexity has global and long-term effects on decision-making, construction, and operations with respect to mega infrastructure construction. Rather, the research indicates that these issues are the most fundamental and important scientific problems of mega infrastructure construction management.

In response to this, Subsequent Narration creates technology and methods to resolve this class of issues through interactions between theory and practice. Furthermore, Subsequent Narration proposes guiding principles at the methodological level that are consistent with complex holistic thinking, and it forms a systematic method based on integrated methodology to recognize, analyze, manage, and control this class of issues.

Four

The basic principle of philosophy states that practices are catalysts of not only the truth of the theory but also the enrichment and development of the theory and the construction of methodology and method system. Accordingly, mega infrastructure construction management theories are rooted in the practice of construction management activities, a premise analogous to the following: just as a tree without roots cannot reap water, theories cannot develop without a source.

Whereas theories must be applied to practice, practice must take guidance from theories, as neither is passive, simple, nor unidirectional. The application of the theory includes consideration, improvement, adjustment, and innovation of the theory. That said, theories combined with practice and theory innovation combined with practical innovation are interactive and intermediary. On the one hand, although practice is the source of the theory, the theory alone cannot claim to fully resolve issues related to practiced mega infrastructure construction management programs. To a certain degree, practice is the great thinker in mega infrastructure construction management theories.

In practice, consideration and innovation of mega infrastructure construction management theories are successive processes that first require reference and learning from previous thought and doctrines that facilitate development and improvement. This process is ongoing and never ending. Any exploration or contribution is merely a marginal accumulation of the innovation process. Even previous efforts, perhaps once perceived as failures, may reflect different implications based on updated results. Therefore, involved parties should not cede to seemingly minor matters and should not be hindered by perceived flawed contributions. Consider, for example, engineering practice, which is infinite, and the related theoretical innovation, which is sustainable. While it is gratifying to conduct important theoretical research and realize achievements in innovation, even small theoretical considerations and explorations should be encouraged and supported, a belief that reflects the fundamental aspects of the author's attitude regarding the basic theories of mega infrastructure construction management in recent decades.

By reflecting on and probing into the mega infrastructure construction management theories, the subsequent content is derived from engineering practice and exhibits good application in practice with respect to, especially, the mega infrastructure construction organization and the decision-making within the organization. In addition, while the content within has practical application, it has not yet had sufficient time to be applied in engineering practice, such as technical management, field integrated control, and normal accidents in safety management. Some content within even refers to aspects derived from theoretical logic, e.g., mega infrastructure construction finance, situational cultivation technology, and federation-based models, an area that is just beginning to be explored. This type of theoretical consideration, where maturities vary and understandings are inconsistent, is an accurate portrayal of the path and the process of major engineering management theory innovation.

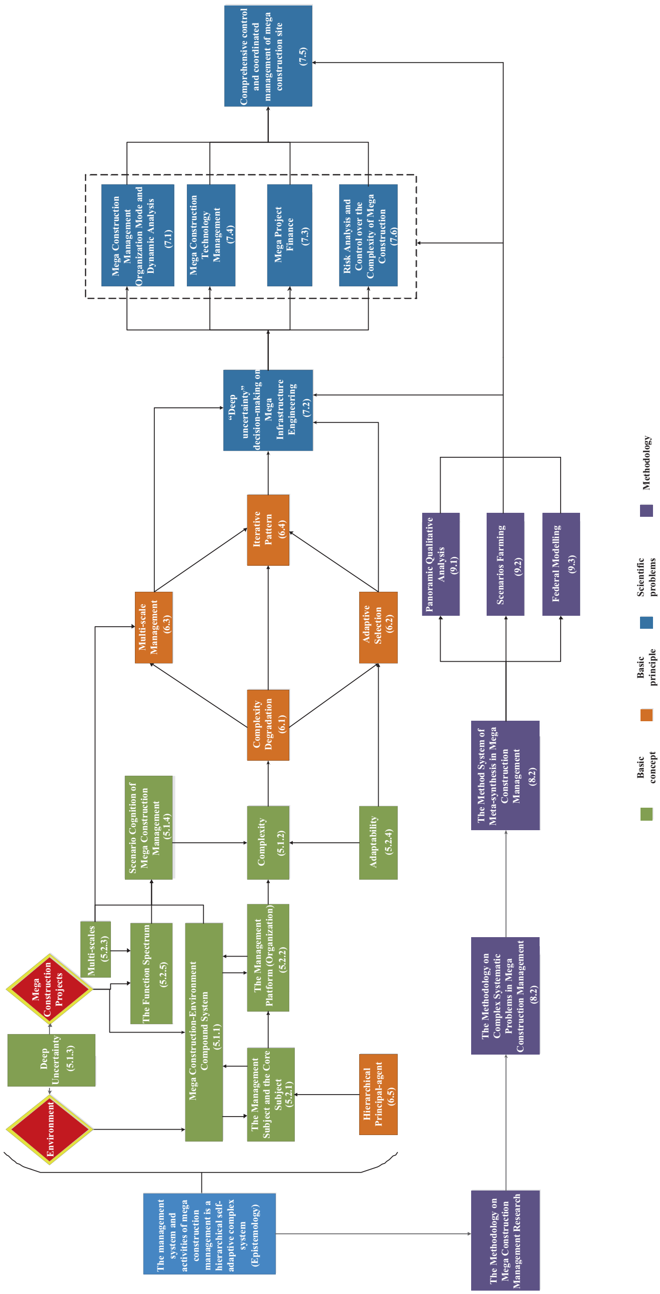
Such consideration reflects Chinese scholars' scientific approach toward seeking the truth from the theories of the innovation process of mega infrastructure construction management. Specifically, theory can neither be fabricated based on illusory materials nor counterfeited during the explorative process. That said, subsequent theory consideration is in the germination stage due to the insufficient support provided by practice. Consequently, as original conditions are subjected, again, to substantial improvements, abundant practice is, again, executed in the future. This could explain why readers question, with respect to this book, the consideration of theory based on different background colors and lack of full expression. For this reason, this book is not considered to be a sound monographic study on mega infrastructure construction management theory. Rather, it is just an interim outcome of the author's consideration and research on mega infrastructure construction management theories.

In fact, the development and improvement of any scientific concepts and principles are the result of germination, growth, and evolution. This is a substantial process inspired, accumulated, modified, and improved by a series of actual phenomena and facts. Any intention aimed at accomplishing an entire task in one stroke is unrealistic and contrary to the laws of the formation of scientific theories, and any theorist or critic must maintain this attitude of tolerance in the spirit of seeking truth from facts.

Although this book may have its deficiencies, the writing and publishing of this book reflect the theoretical considerations of Chinese scholars' mega infrastructure construction management practices in recent decades, and it summarizes the interim exploration of the Chinese construction management scholars' transition from Repeating Narration to Subsequent Narration.

Finally, whereas this book is about the exploration of the mega infrastructure construction management theory and the development of a basic theoretical system, with respect to management connotation, it also considers the epistemology and methodology of the overall levels, the systematic revelations, and the complex essence of management activities. Furthermore, the statements of thought principles, formations of management theories, designs of scientific connotation, structures of management theory systems, and integration and progressive arrangement of core concepts, basic principles, scientific problems, and methodology in management theory systems have certain references within the broader context of management beyond those of the mega infrastructure construction management areas. Therefore, we contend that this serves as a contribution to the study of mega construction management theories and the development of those management theories.

Nanjing, China Zhaohan Sheng



Basic Theory System of Mega Infrastructure Construction Management Developed and Presented in This Book: Basic Concepts, Principles, Scientific Problems and Methodology

Contents

Part I
Engineering, Mega Infrastructure Construction, and Mega Infrastructure Construction Management

This section consists of two chapters, and the content is divided into two parts.

In Chap. 1, the author first provides a detailed elaboration of the concept of significant engineering, the major subject of study in this book, with the intent to clarify the definition of significant engineering, and its essential characteristics. This serves to pave the way for the further abstraction of broader scientific intentions with respect to mega infrastructure construction.

In Chap. 2, the author first analyzes the essential features of mega infrastructure construction management activities by comparing the features of construction management activities with those of mega infrastructure construction management activities. Based on the fundamental principles of system science, the author concludes the analyses and puts forward a development rule that as construction management develops toward mega infrastructure construction management, the essential attributes of construction management gradually evolve from systematicness to complexity.

On this basis, the author further analyzes the important scientific connotations, such as the general complexity of mega infrastructure construction management, in the discourse of a complex system and proposes a new cognitive paradigm for discerning mega infrastructure construction management, thus laying a solid foundation for understanding mega infrastructure construction and mega infrastructure construction management in general.

Chapter 1
A Basic Definition of Mega Infrastructure Construction

A concept is a general idea or a summary of something or of some certain processes. As such, it takes shape in one's mind as the individual delves into a specific problem. A concept can be an abstraction of the essence and characteristics of a subject being studied, or it can be the delimitation of the scope in which a research question is discussed.

Clear and explicit concepts are of great importance to theoretical studies, especially with respect to the definition of those fundamental subjects in theoretical studies. To avoid any arbitrary or ambiguous interpretation of those important concepts, it is essential to identify the precise meanings of the concepts that will be used in the studies.

In this book, the most important and fundamental concept is that of mega infrastructure construction. Despite the fact that general agreements and consensus over this concept and its derivative concept mega infrastructure construction management have been reached during the years of construction practices, for the sake of academic rigor in theoretical studies, the author provides basic and essential definitions of the fundamental concepts used in this book, including mega infrastructure construction and mega infrastructure construction management.

1.1 Engineering and Project

1.1.1 Engineering

Dating back to the age of ancient civilization, man has engaged in all types of material production activities, such as hunting, fishing, poultry raising, crop planting, and fruit gathering. Man also initiated various entity-creating and entity-using activities. For example, people have built buildings, roads, dams, bridges, etc. all with the aim to meet the most basic material needs for living. Originally, most objects

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people used in the production practices were those already existing in the natural world. However, an entity-creating process entails consciously creating artificial entities or remolding entities already existing in nature to better meet the needs of humans. In turn, the consequences of such remolding reshape nature to some extent. In this sense, the entity-creating activities found in the practical activities of man as far back as ancient times can be perceived as the origin of modern engineering activities.

Man's entity-creating activities, including those that change the original traits of already extant entities, are complete processes that involve generating entity-creating ideas, formulating the design plans, organizing and implementing the development of the activities, and overseeing the final completion of the artificial entities intended to be created. This entire creation process demonstrates that the concept of engineering mainly refers to a process of creating artificial objects or entities based on certain human intentions (Sheng and You 2007; Sheng et al. 2008). At times, people may use the word "engineering" to refer to those artificial objects or entities completed during such engineering activities. It is only a habitual way of phrasing in Chinese. For example, in the sentence, "The Great Wall of China is a great engineering project," the term "engineering project" refers to the real-world entity, "the Great Wall."

With the enrichment of man's entity-creating activities and the gradual abstraction of man's cognition and perception of the world, the definition of engineering has evolved along two paths.

Since man's entity-creating engineering activities primarily began with activities related to the construction of buildings, roads, and dams, entity creating in the early times was characterized by civil engineering features. In consideration of the purposes of civil engineering, it is necessary to set clear goals for entity-creating engineering activities and to carry such activities through to the end. With the development and expansion of man's practical activities, the scope of engineering activities has expanded broadly. It is generally accepted that, in a given field, human activities with complete engineering processes and specific purposes could be viewed as engineering activities. Thus, numerous concepts related to engineering have been espoused over the years, such as mechanical engineering, chemical engineering, electronic engineering, and computer engineering. As different science disciplines are integrated into the education systems, these engineering concepts have gradually evolved into corresponding disciplinary concepts in college education.

With further social and technological advancements, humans have broadened even further the entity-creating concept of engineering to cover more fields, such as social science, technology, psychology, culture, education, and logics, thereby generating concepts that embrace richer meanings, such as software engineering and systems engineering.

The definition of the concept of engineering, which, initially, referred to civil engineering and hydraulic engineering, has evolved and broadened considerably, now including fields such as mechanics, electronics, and information science. Furthermore, the sphere of engineering has been broadened from physical engineering to semi-physical engineering and nonphysical engineering. This development reveals the constant progress of man's entity-creating practices and the continuous expansion of the scope of such practices. The ongoing evolution of this concept enables people to describe and understand those entity-creating practices and processes that are unique to humans. Provided that the basic meaning of engineering is understood and the relative background information is taken into consideration, the exact meaning of engineering in a specific context can be stated clearly and accurately.

In accordance with the above, engineering, including mega infrastructure construction, as examined and discussed herein, refers only to the physical entity-creating engineerings, such as highways, bridges, and hydraulics.

1.1.2 Project

The concept of project is closely related to that of engineering. Generally speaking, *a project refers to a series of special and complicated activities that are correlated with each other. These activities usually share a clear objective or purpose and require the use of designated resources, the adherence to certain standards, and clearly specified time periods and budgets.* Accordingly, a project can be the building of a house, the development of a product, or the holding of an event.

As the objectives and purposes of different projects differ significantly from one another, they are divided into two types, namely, the physical and the nonphysical. With respect to the physical objectives, the definition of a project is basically the same as that of physical entity-creating engineering activities, without substantial differences between them. Therefore, it is safe to say the following:

1. In circumstances where it is not stated clearly whether a project is a physical or nonphysical one, the project may include both semi-physical and nonphysical activities. Therefore, as a rule, the concept of project usually takes on a broader meaning than that of engineering, which focuses more on entity-creating activities, as, in many cases, the project may refer to activities that extend beyond the entity-creating scope. For example, there are cultural and educational projects, such as the Hope Project, which is a national project founded in China to support rural education, and the 211 Project, which is one of China's national projects established to promote college education, that extend beyond the scope of entity creation.
2. The concept of project places greater emphasis on the uniqueness of an activity as well as on how to acquire and use the resources, how to distribute the staff and assign different tasks to different people, and how to orderly arrange different activities within a project. From this perspective, the concept of project places greater value on the on-site operations and the organization of a specific activity to a greater extent than engineering, which places more emphasis on generalizing the features of human activities that create artificial entities at the macro and global levels.

3. Because a project highlights the targeted activities of the mission, organization, and operation, people tend to use the term project more so than they do the term engineering when they need to break the job down into detailed tasks and identify the specific operations. This is a popular and traditional way to differentiate these two concepts in the construction industry. In fact, this distinction could be viewed as a habitual use of words with little special meaning attached to it.

1.2 Significant Engineering and Mega Infrastructure Construction

1.2.1 Significant Engineering

With the development of human society and the advancement of science and technology, man's construction activities have embraced diverse features, including complex environmental conditions, projects of enormous scale, advanced technology, tremendous investments, long construction periods, long project life cycles, significant and continued impact on the socioeconomic environment, etc., all of which have become especially prominent in the past century. Such constructions have resulted in new living environments or remarkably improved old ones for humans, laid a solid foundation for the sustainable development of human society and human civilization, and gradually driven the concept of significant engineering. Basic features such as huge scale and significant impact comprise the rational and intuitive understanding people have of significant engineering.

In fact, the key to understanding the concept of significant engineering lies in the perception of the word "significant." For example, in terms of construction investment, the Federal Highway Administration of the USA once stipulated that constructions with costs exceeding one billion dollars would be viewed as mega constructions, while the Norwegian government set the cost baseline of significant engineering projects at 60 million euros. Given the varied economic conditions of different countries, determining whether a construction is a mega construction simply based on the amount of investment would lead to much discrepancy, thus demonstrating that it is not feasible to define significant engineering as a measurable concept and measure it through certain quantitative methods. Therefore, with long-term construction practices as a basis, people are more inclined to summarize the basic features of significant engineering from different perspectives and different levels before forming a descriptive definition. This intuitive way of interpreting and understanding significant engineering is widely accepted because whether a construction is perceived as significant is, to a large degree, dependent on people's understanding of the construction. In general, the public has reached a consensus that a significant engineering construction is large scale and has great significance.

Viewed from the extensiveness of the functions that engineering can provide, entity-creating significant engineering constructions are divided into the following types:

1. Mega scientific and technological engineering. This refers to those engineering constructions that focus on exploring and discovering significant scientific rules or achieving major technological breakthroughs, with an aim to accomplish major scientific and technological development goals in limited periods of time. These types of engineerings, e.g., gene study projects and material microstructure study projects that are jointly conducted by multiple countries or spacecraft projects conducted by one or multiple countries, will have global influences on and provide an overall impetus to social development by promoting man's understanding of natural rules, contributing to breakthroughs in key technologies, enhancing the strategic competitiveness of specific industries, etc.
2. Mega military and national defense engineering. This refers to those significant engineerings conducted by separate countries or alliances of countries with a primary focus on the research and development of weaponry and military equipment for the purpose of safeguarding defense security or reinforcing national military strength. For instance, the National Missile Defense (NMD) system developed by the USA and the Global Navigation Satellite System (GLONASS) developed by Russia fall into this category.
3. Mega infrastructure construction. The most basic meaning of infrastructure is fundamentality and "providing the foundation for social development." The *World Development Report 1994* (1994) published by the World Bank once proposed that infrastructure is defined as the "permanent constructions, equipment, facilities and the services they provide for people's living and for social production." One type of infrastructure is known as economic infrastructure and includes urban public utilities, transportation facilities (e.g., highways, ports, and airports), public constructions (e.g., dams and hydraulic facilities), etc. A second type of infrastructure is termed social infrastructure and includes educational facilities, cultural facilities, and health-care facilities. Physical infrastructure projects are projects that directly meet and satisfy the basic survival and daily living needs of humans. Such infrastructure projects are generally of large scales and have great significance. Thus, it is appropriate that such projects belong to a special category, specifically, mega infrastructure construction. Comparatively speaking, mega infrastructure construction, the primary purposes of which are improving people's lives and facilitating social development, is more common than the other two types of significant engineering, namely, mega scientific and technological engineering and mega military and national defense engineering. For example, China's South-North Water Diversion Project, the Three Gorges Dam Project, and the Hong Kong-Zhuhai-Macau Bridge project are all mega infrastructure constructions vital to national well-being and to the livelihood of the people.

1.2.2 Mega Infrastructure Construction

Among the three types of significant engineering previously introduced, significant scientific and technological engineering and mega military and national defense engineering have special requirements and unique operation procedures with respect to the environment, purpose, subject, decision-making, and implementation of engineering. Furthermore, as relevant information is highly confidential, most such engineerings would cause a state of information asymmetry with respect to the public. Therefore, studies on such engineerings may require special research paths and research methods. Comparatively, mega infrastructure constructions closely related to people's livelihood not only fully reflect the essential features of significant engineering but also profoundly embody the basic rules of economics, management, and many other disciplines. Because there are enormous relevant information available to the public and enough samples for exploration, pursuing theoretical studies of these important mega infrastructure constructions to seek rational explanations of the common phenomena in such projects and to uncover the underlying general rules is of great academic value and universal practical significance.

China is currently the largest developing country in the world. With a huge population to support and to promote social and economic development and advance strategies, such as urbanization, for quite a long period into the future, China must strive to increase housing construction and accelerate the development of infrastructure such as highways, railroads, bridges, and communication facilities as well as improve the environment by implementing hydraulic engineering projects and environmental protection projects. This reality positions China as a major country in the world in the field of infrastructure development.

To support this argument, more evidence is found in an article published by *The Washington Post* on March 24, 2015. In this article, it was reported that China used more cement during the last 3 years than the USA had used over the course of the entire twentieth century. Specifically, America's cement consumption during the last century totaled approximately 4.4 billion metric tons, while China used approximately 6.4 billion metric tons from 2011 to 2013 (Ana 2015). Officials of the China Cement Association confirmed this figure in an interview with the *Global Times* on March 25, 2015, and explained that this could be attributed to China's current rapid development needs in various areas (Xing and Chen 2015).

A review of numerous projects indicates that mega infrastructure constructions refer to those projects that involve a wide range of activities and a great deal of construction and are recognized as the type of projects that have the closest relationships with the public. The most important basic features of mega infrastructure constructions are as follows:

1. Generally, the state (government) is the major decision-maker and investor for the mega infrastructure construction. For this reason, the state (government) often plays a leading role in the process of the mega infrastructure construction and predominantly controls the decisions with respect to major issues such as

whether a project should be approved, whether a project should be funded, and how a project should be carried out (Cairns 2004).

2. Mega infrastructure constructions usually have huge construction scales. The projects, for the most part, are conducted in vast areas and on large scales. For example, an inundation area, i.e., a 632 km^2 area of land subject to flooding, is the result of the Three Gorges Dam Project and involves more than 20 cities and towns that are inhabited by a total of 850 thousand residents. Considering such factors as resettlement for the second time, the dynamic population resettled under this project amounted to 1.13 million people (Shi et al. 2011). In addition, the Three Gorges Dam Project was planned to be implemented in three phases over a total construction period of 17 years at a gross investment of RMB 332 billion (Wang 1999). In another example, the West-East Gas Pipeline Project, which runs eastward from the Tarim gas field in Xinjiang to Shanghai, has a main pipeline that extends over 4000 km, at a total investment of RMB 120 billion in the first phase of the project (Wu 2004).
3. Mega infrastructure constructions are characterized by complex environmental conditions. Mega infrastructure constructions are often located in places that have complex or even adverse environmental conditions. For example, the Qinghai-Tibet Railway project is a 1956 km railroad that begins in Xining, Qinghai province, and extends to Lhasa, Tibet Autonomous Region. The main portion of the project is located in the Tibetan Plateau, which is known as "the roof of the world" and "the third pole of the world" (Sun 2005a). As part of the project, there is 960 km of railroads built in areas with average elevations exceeding 4000 m and thus featuring anoxic atmosphere and extremely low temperatures as well as complex and changeable climates. Moreover, approximately 550 km of railroad was constructed on continuous fragile permafrost areas that are characterized by persistent low temperatures and weak frozen soil layers. Thus, another challenge in this railway project was the construction of tunnels at the world's highest elevation and across the longest miles of permafrost in the world (Sun 2005a, b).
4. Mega infrastructure constructions are characterized by their significant and far-reaching impacts on the social and economic developments of a region. Mega infrastructure constructions are generally implemented for promoting the social progress and economic growth of a specific area or enhancing the living environment for a society over the long term. Therefore, the targets of mega infrastructure constructions must provide powerful positive energy for regional developments both socially and economically. However, it must be noted that not all of the goals set for mega infrastructure constructions could be accomplished. In fact, decisions with inadequate planning or severe faults in decision-making could result in undesirable consequences. Given the far-reaching influence that mega infrastructure constructions may exert on the social and economic development of a region, once such failures occur, immense long-term and irreversible damage may ensue. The last few decades have witnessed many such failures in mega infrastructure projects around the world.

5. Mega infrastructure constructions usually have long life cycles. For multiple reasons, including vast construction scales and complex environmental and technical conditions, a mega infrastructure construction, from the initial design to the final completion, often extends over many years or even decades. Furthermore, once a completed construction comes into service, it can endure for decades or even centuries, i.e., until the end of its life cycle. The possibility of such long life cycles determines that a mega infrastructure construction may be divided into different sections that are to be carried out in different phases. More importantly, a long life cycle determines that during the implementation of a project, especially during the realization process of its original goals, many uncertainties in the social and economic environments, as well as in the changing natural environments, would occur that require the functionality of a mega infrastructure project to be robust and stable over a long period of time (Priemus et al. 2008). These requirements pose great challenges not only with respect to the quality of mega infrastructure project constructions but also with respect to the quality of the decision-making for such mega infrastructure constructions.
6. Various partnerships are engaged in the implementation of mega infrastructure construction projects. In a mega infrastructure construction project, different partnerships may prefer different project goals and pursue different interests, resulting in conflict and competition among the various partners during the decision-making process (Marrewijk et al. 2008; Woodgate 2009; Mok et al. 2014; Yang et al. 2009, 2011). For example, proactive public participation may lead to complicated relationships among the different stakeholders in a mega infrastructure construction (Zou et al. 2014).

These features, while not representative of all of the essential characteristics of mega infrastructure constructions, embody the common understanding people have of the typical features of mega infrastructure construction and their perceptions of its scientific implications. *Therefore, in a general sense, these features, as a whole, can be perceived as the descriptive definition of mega infrastructure construction.*

Significant engineering, as discussed in the following chapters and as the major subject of the study in this book, refers to mega infrastructure construction.

The features previously described herein suggest that mega infrastructure constructions have essential features that are not found (or, if found, are neither distinctive nor prominent) in other common projects. In fact, together, these features have formed a new entity-creating activity pattern, that of mega infrastructure construction practices, and have profoundly broadened and transformed man's understanding of engineering. More importantly, it is widely acknowledged that the essential features and attributes of mega infrastructure construction have contributed to the establishment of a new type of cognitive rule. This rule compels people to recognize that mega infrastructure construction is a unique type of engineering or engineering activity process that is distinct from other engineering activities; moreover, it will further exert a profound impact on future mega infrastructure construction management activities and future theoretical studies of mega infrastructure construction management.

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Chapter 2
Mega Infrastructure Construction Management

Construction management activities are critical and indispensable parts of entity-creating construction activities. Great projects require not only construction but also management. Mega infrastructure construction management activities, similar to mega entity-creating construction activities, are faced with various new phenomena, new problems, and new rules, all of which require people to expand their thinking and develop new cognitions.

2.1 Construction Management: Overview

In ancient times, people could conduct simple, small-scale construction activities. Usually, one person could only complete the work required of a rather simple entity-creating construction activity. However, as the scale of construction activities increasingly expanded, it became increasingly more difficult for one person to complete, independently, the work required to complete the entire construction activity. Under such circumstances, people tended to collaborate with each other and form specific groups to complete specific aspects of the activity. Thus, with their collective power and intelligence, humans were able to overcome various difficulties and complete complex constructions. As a result, this trend for collaboration grew increasingly more popular (Cicmil et al. 2006).

Learning from these practical activities, humans came to realize that in collective entity-creating construction activities, they needed to become more organized and needed to distribute the work and divide the entity-creating construction process into different stages that were sequentially connected with one another. The division of work better ensured the accomplishment of the construction objectives and resulted in the more efficient and sequential completion of the construction activities. Furthermore, one or more persons would separate from the specific and direct

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entity-creating construction work and engage, instead, in those activities designed to make the entity-creating construction activities more organized and more efficient (Capka 2004). Such activities could be described as follows:

When different groups of people jointly participate in a certain construction activity, according to the entity-creating environment and the preset construction objectives, one or more persons specialize in the planning, sourcing, and distribution of resources necessary for entity creation. In this capacity, they allocate and organize assignments for the various working groups and teams and coordinate relations among the various groups and assignments to better organize the entity-creating practices and make them more efficient. These types of activities are presented as construction management activities; construction management is short for construction management activities.

The implications of construction management are elaborated as follows:

1. Man's construction management activities stem from entity-creating construction activities, and as such, they generate an impact on entity-creating construction activities. In turn, these two types of activities are closely related to each other. Whereas constructions are created by humans during entity-creating activities, construction management plays the role of integration, adjusting, coordination, and regulation of the actions and relationships between people, between people and things, and between things.

   Accordingly, humans could not live without entity-creating constructions, and entity-creating constructions could not be carried out without construction management.
2. Construction management is composed of a series of holistic practical activities that are conducted during the entity-creating construction process. Similar to other management activities, construction management activities are also characterized by a complete process that involves basic elements such as management objectives, subject organizations, problems, and environments. A complicated management activity could be conducted at different levels and in several parts that are relatively independent of one another (Wang et al. 2014).
3. Construction management activities are usually conducted simultaneously with relevant construction activities. That is, once a construction activity begins, the corresponding construction management activities also begin. Furthermore, once the construction activity is terminated, the corresponding construction management activities also cease. However, as man's construction activities become increasingly more complex, it is necessary, in relevant construction management activities, to conceive early construction management ideas, make early-stage decisions, plan the project, present the arguments, and proceed with the operation management and post assessments so that the construction management activities can fulfill and move forward or draw back accordingly, thus extending both ends of the life cycle of a certain construction.
4. Any entity-creating construction is specific and unique, and there are no two constructions that are exactly the same. Thus, as a consequence, different construction management activities also enjoy their unique features, which means that there is

no single construction management model that could solve all problems or be valid in every type of entity-creating construction activity. On the contrary, every specific construction management activity changes over time and is conducted in different ways for different reasons by different people in different places.

5. Even though there is a high degree of similarity between two constructions, the detailed construction management requirements are necessarily different in each case. This is not simply because every construction has its own unique and distinctive features. In essence, construction management is a type of activity engaged in by some people, namely, the subjects, who then act on some other people, namely, the objects, an interaction that indicates that the objectives of construction management are integrated not only with the value judgments and value orientations of people but also with the cultural dispositions, including the intellectual factors such as the personal preferences, behaviors, emotions, and personal habits of people. In other words, the essence of construction management is people-oriented or people-centered activities. Therefore, it is unadvisable in construction management activities to place greater emphasis on the thing than on the person or to value the things while ignoring the person (Cheng et al. 2004).
6. Construction management embraces diversified and rich contents. Therefore, to complete many of the management tasks, there must be corresponding technologies, methods, and approaches. In this sense, construction management should be both feasible and actionable to ensure that it is both effective and cost efficient. Thus, when there are different models of construction management from which to choose, the appropriate and economical ones should be selected over the superfluous and lavish ones (Qi and Liu 2012).
7. As human society advances, humans become increasingly more skilled in entity-creating constructions, and thus, the connotations of construction management also evolve and become richer, presenting an exuberant picture of new managerial ideas, knowledge, and approaches "springing up like mushrooms after rain."
8. Because of the rich construction management practices, people have long conducted studies on construction management and have established corresponding education systems and disciplinary research systems. Studies regarding the theories, approaches, and applications of construction management have never been as numerous and prosperous as they are today (Baccarini 1996).

2.2 Mega Infrastructure Construction Management: Overview

As stated previously, now that mega infrastructure construction enjoys essential characteristics unique to itself, the corresponding management activities will inevitably encounter many new conditions that differ from those of construction management activities.

Accordingly, these fundamental conditions are reviewed one by one in consideration of the basic factors of construction management activities, from which we can clarify the significant differences between mega infrastructure construction management and construction management.

The first factor is the management environment Because mega infrastructure constructions usually cover large geographical areas and wide spaces, the social, economic, and natural environments of a certain construction would not only change dynamically during the long life cycle of a construction but would also encounter various complex phenomena such as evolution and sudden changes (Stergiopoulos et al. 2016). As a consequence, these factors may generate significant impact on the function design and construction of a mega infrastructure construction, as well as on the construction quality and function stability during the long post-construction period. For example, the construction process may be suspended because of unstable political and social environments; unexpected economic turmoil could result in fund chain breaks; and drastic changes in the natural environment could disrupt the normal performance of the functions a construction is designed to perform (Salet et al. 2013). Thus, complicated management environments make it increasingly difficult in mega infrastructure construction management to produce high-quality constructions and develop solid construction functions.

The second factor is the management body A management body of a mega infrastructure construction refers to a management entity that is composed of multiple stakeholders who possess decision-making authority, property rights, construction rights, supervision rights, and the right of discourse. Such stakeholders include the government, project owners, designers, contractors, suppliers, supervisors, scientific researchers, the public, etc. This group, which is composed of numerous mega infrastructure construction management subjects, would be large in scale and include numerous people who may have diversified values. Nonetheless, the members share a common goal, which is to construct and manage successfully a mega infrastructure construction. To achieve this, the members will make efforts to perform their respective roles in different phases of the construction management process. However, at the same time, different value preferences among the group members may trigger different interest demands and conflicts with respect to the activities (Shi et al. 2015). This situation will not only make it difficult for the management body to reach a consensus and establish a common goal but also generate contradictions and competition in issues involving their interests. Such circumstances call for strong leadership and coordination capacity as well as effective management models and procedures on the part of the mega infrastructure construction management body. Furthermore, it is of great importance to ensure that the management subjects' actions conform to standards and to prevent the body from taking divergent actions (Miller et al. 2000). For example, at the site of a mega infrastructure construction project, because the coordination between the design party and the construction party has a direct bearing on on-site technical interactions, a failure in coordination may result in conflicts related to interests and responsibilities between the two parties. Moreover, in some cases, these conflicts can be extremely tense and difficult to defuse.

That said, in the face of complex mega infrastructure construction management environments and complex problems, the management subjects tend to possess inadequate knowledge, experience, and competence, a situation that requires the management subjects to enhance their management capabilities through self-directed learning. From another perspective, the lack of knowledge and skills creates further challenges when coordinating the actions of the various management subjects because the self-directed learning activities cannot be interpreted as easily as behaviors of individual project owners or certain managers. Instead, self-directed learning refers to improving management capabilities by reorganizing the original group of subjects or organizing a new group. As a result, it will inevitably add great complexity to the behavioral models and organizational models of the mega infrastructure construction management subjects.

The third factor is the management issue Compared with construction management, mega infrastructure construction management has far more management issues that are also more complex than those of construction management. Though these complicated issues may only represent a small fraction of all management issues, they require managers to expend substantial amounts of time and energy. More importantly, however, if one of the issues is not settled smoothly and efficiently, the overall construction and operation of the mega infrastructure construction may be severely negatively affected (Bertolini and Salet 2008).

The aforementioned issue can be interpreted from three perspectives.

1. Such management issues generally involve knowledge of multiple disciplines and fields. For example, the location of a mega transportation infrastructure construction should not only consider the prospect of improving traffic conditions but also take into account the social and economic effects on the surrounding areas. In addition, the potential impacts that the natural environments, such as the geological and hydrological environments, may have on the engineering construction, as well as whether the construction would damage the natural environment, must be considered. Under such circumstances, it is definitely necessary for experts from multiple fields to integrate their professional knowledge to solve such management issues (Lu 2009).
2. The boundaries between the management issues are usually blurred. With respect to different factors related to a certain issue, besides clear input/output relations between one another, there are also association relations that cannot yet be determined with certainty, and there are not only overt and identifiable association relations but also covert and unidentifiable association relations. Moreover, some relations or relevant factors identified and confirmed by us may change under the influence of other factors during the actual functioning process, leaving people confused and uncertain about the issues in question (Fabbro et al. 2015).

3. It is usually difficult to describe the management issues using a clear and explicit structured method (model). In fact, mega infrastructure construction management often involves social and economic factors, engineering technological factors, and human behaviors and cultural values. Of these factors, engineering technological factors are dominated by natural sciences and technological principles, making it possible to describe these specific factors via certain structured models. However, in most cases, factors such as human behaviors and cultural values can only be described by unstructured models (Liang and Sheng 2015). From this perspective, it is necessary to use a combination of structured, semi-structured, and even unstructured models to clearly and accurately describe these types of management issue. This integrated approach not only increases the complexity of modeling these management issues but also makes the integration of different types of models far more difficult.

A typical example of this is the construction of China's South-North Water Transfer Project, a giant inter-basin water transfer project of strategic significance designed to divert water from the upper, middle, and lower reaches of the Yangtze River to the northeast areas, the Huai-Hai Plain area, and the northwest areas that are facing serious water shortages. The water is diverted through three routes, namely, the eastern, central, and western routes, in consideration of the topographic features of the Chinese territory. The water transfer routes of this project pass through seven middle and western provinces from south to north for a total transfer distance that exceeds 1000 km. In terms of the relationships among the key construction factors, what must be done is to establish the transfer waterways and divert clean water from the south directly to the north. However, in reality, judging from the following analyses, it is much more complicated than that:

1. In China, water, especially clean water, is an extremely precious and scarce resource. If a sense of water saving is not fostered throughout the entire society and if conditions such as extensive use of water and serious water wasting continue without improvement and change, the benefits of the project will undoubtedly be counteracted. Thus, improving the conditions calls for a change in industrial and agricultural production modes, as well as in people's modes of living. Without change, the limited clean water to be transferred, in the end, will serve no productive purpose.
2. At present, the water sources of the southern region's water supply face serious pollution. For instance, as the pollution increasingly worsens in the nearshore areas of the Yangtze River in the east and central regions, the water supply for the local cities faces serious threats of pollution. In addition to taking pollution abatement measures, it is also critical to keep the water sources clean and take precautions against the northward spread of biological diseases caused by pollution. On the other hand, the western water supply regions of the project are located in the upper reaches of the Yangtze River, where the degradation and desertification of the grasslands are in very serious conditions. Thus, water transfer provides no benefits to water conservation, and even worse, it may severely jeopardize the ecological shelter zones in the upper reaches of the Yangtze River.

3. The South-North Water Transfer Project is a 1000 km passageway, and the regions along the transfer routes, as well as the water-receiving regions, all face serious water pollution and ecological environmental damage, results that urgently demand effective solutions.
4. In addition to taking measures to directly deal with the water pollution in the water source regions, a long-term sustainable adjustment to the economic structure that includes limiting the migrations of high polluting and high water consumption enterprises to this area to prevent new threats to the already fragile ecological environment in the water supply areas is needed.

It is evident that the construction management of the South-North Water Transfer Project involves not only building water transfer channels and establishing direct input/output relationships between the water supply areas and the water-receiving areas but also complicated associations and relationships among the society, the economy, and the water ecosystem, all of which have too much causality and relevance. These associations and relationships extend far beyond the single realm of hydraulic engineering technical issues. In fact, they have evolved and resulted in a huge cluster of issues that span environmental governance, social and economic development, industrial structure adjustment, regional development strategies, and even the transformation of people's living habits and cultural philosophies. All these factors will inevitably exert enormous influence on the target design, scheme design, interest coordination among multiple subjects, and project benefit evaluations of the South-North Water Transfer Project.

Thus, for the South-North Water Transfer Project to function effectively in the long term, it is essential to foster better management ideas and managing schemes. For example, could the water-receiving areas regurgitate the feeding of the water supply areas? Only if the water-receiving areas can maintain fairly good ecological environments after completing the transformation of the development patterns and living modes can the original intentions of the South-North Water Transfer Project benefitting both the country and the people be realized in the long term.

The fourth factor is management organization For normal constructions, given that the management problems are relatively simple and the management body is sufficiently competent, in most cases, it would be enough to plan and establish a management organization and allow this organization to address all the management issues throughout the construction management process from the beginning to the end as they arise. However, with respect to mega infrastructure construction management, the management body may be confronted with significantly complicated problems, and thus, it is often the case that the management body is not capable or sufficiently competent to address these problems. Therefore, in practice, it is difficult to establish a single construction management organization that can guarantee that it can analyze and master all types of management problems that occur during the construction management process. As a result, a mega infrastructure construction management organization should have certain flexibility and be able to adapt to potential adjustments in the management process, including changing the composition of the group and changing the management mechanism and procedures to improve the overall management capacity (Ponzini 2011). For example, initially, the relationship between the owner and the research and development institutes is usually a direct principal-agent relationship. In the subsequent phases, however, the principal-agent relationship is formed indirectly through the designers and the contractors. Similarly, the owners and the subcontractors may first establish connections with each other through the contractors but later establish direct professional subcontracting relations, etc.

The fifth factor is the management objective Solving management problems is always management objective oriented. Regarding mega infrastructure construction management, due to the long construction life cycle, the management objectives may differ based on different time scales. In addition, since mega infrastructure constructions significantly impact the social and economic environments, the management objectives are reflected differently in different areas. Thus, it is not difficult to see that these objectives, which have different dimensions and/or objectives and the same dimensions but different scales, have not only formed multilayered, multidimensional, and multi-scale objective systems but also caused problems when describing the objectives, such as vagueness, uncertainty, conflict, and immeasurability of the objectives, thereby multiplying the difficulties when conducting a comprehensive analysis and evaluation of these objectives (Gao and Liu 2005; Md. Masrom et al. 2015). For instance, the basic objectives of project bidding and project procurement are to provide excellent contractors, high-quality construction materials, and appropriate technologies. Therefore, in the bidding and the procurement processes, it is necessary to consider many factors, such as price, quality, and corporate reputation. However, in practice, what are most urgently needed for mega infrastructure constructions are reliable technologies. Without such technologies, objectives such as the quality, safety, and cost efficiency of mega infrastructure constructions cannot be realized. For this reason, during the actual bidding and procurement processes of mega infrastructure constructions, priority must be given to advanced and reliable technologies. This differs remarkably from other construction bidding evaluations in which the business points constitute the greater proportion. In mega infrastructure construction management, this technology first principle should be well implemented in the bidding evaluation system. In addition, it is common that different management objectives of a certain mega infrastructure construction conflict with one another and that some of those objectives are difficult to measure.

The sixth factor is the management program The management program refers to the solutions, plans, approaches, and methods proposed to address the various mega infrastructure construction management problems. For these relatively simple problems in mega infrastructure construction management, the formation of a management program differs little from those of other constructions. However, for highly complex problems, the development path of a management program is quite different.

First, as a result of humans' cognitive rules, the management subjects' understanding of a complex problem undergoes a certain process, i.e., from knowing nothing to knowing a little, from knowing a little to knowing some, from knowing some to knowing superficially, and from knowing superficially to knowing profoundly. This process not only reflects the depth of the subjects' personal cognition of the problem but also is a process in which the management body, as a group, can reach consensus (Guo et al. 2012).

Therefore, the managing bodies of mega infrastructure constructions experience an exploratory trial-and-error process as they work together to develop a management program. During this process, the management programs are commonly not formed immediately and are not presented as optimal programs. Rather, a management program is usually confirmed after numerous comparisons with and revisions and improvements of several alternative management programs based on the depth and accuracy of the management group's understanding of the problems to be solved (Salet et al. 2013). In other words, the formation process of a management program goes through incremental iterations, approximations, and convergences before eventually resulting in the final program. It begins with periodic draft solutions and gradually develops from vagueness to clarity, from partiality to comprehensiveness, and from lower quality to higher quality.

Accordingly, during the formation of the scheme, it is inevitable that many new and complicated links and interfaces will appear. For example, more coordination and communication are needed between the managing subjects; more revisions and version comparisons are needed as the draft schemes iterate; different types of information are integrated effectively; and overall evaluations and optimizations of the schemes, such as cost, time efficiency, and quality, are performed.

As illustrated in the following pattern, during the process of selecting a program, the initial program may be found to be undesirable in terms of overall technological and economic effects, or it may be determined that the design objectives deviate from the original project intentions. In such cases, the scheme study should go back to the previous phase and develop a new scheme for further in-depth study to identify a final program (Fig. 2.1).

To sum up, regardless of which factor of management activities we select for analysis, we find that there are conspicuous differences between mega infrastructure construction management activities and other construction management activities and that many new intuitive features have replaced former features. Moreover, these features cannot be viewed as the quantitative accumulation of the same features of construction management activities, such as larger activity scales and more subjects. In fact, they reveal that new properties arise in management activities, such as the flexibility and adaptability of management organizations and the iterative patterns of developing managing schemes. The facts have proven that these new properties reflect the significant changes in scientific implications from construction management to mega infrastructure construction management. At the same time, these changes, besides inducing a series of management transformations, also require us to conduct new and in-depth explorations of mega infrastructure construction management practices and theories.

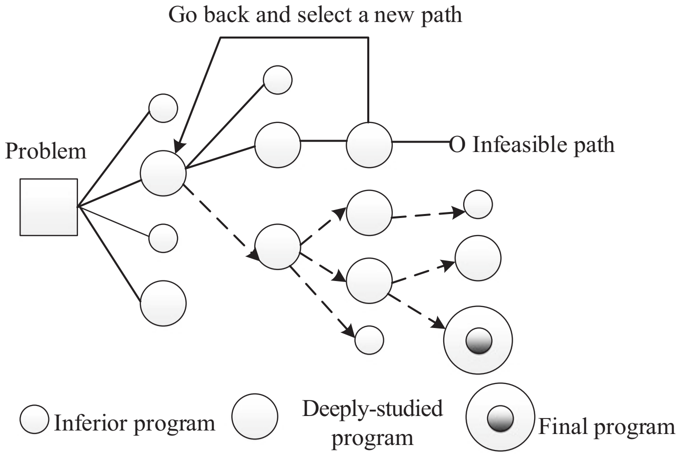

Fig. 2.1 Program comparisons based on feedback and supplements

2.3 Construction Management to Mega Infrastructure Construction Management: Systematicness to Complexity

After comparing the management of mega infrastructure construction and construction and identifying various intuitive differences between the two in the previous section, a next step that is related to the understanding of the scientific connotation of construction management and mega infrastructure construction is to determine the respective properties or natures of the two constructions.

Since construction management is rooted in construction, while mega infrastructure construction is rooted in mega infrastructure construction, to identify those respective properties, we should first clarify the properties of construction and mega infrastructure construction. The properties of an entity are the unique characteristics and features that the entity reveals within its own existence and operation and that provide the basic difference between it and other things. Only after being aware of the essence of these features and characteristics can people have an understanding of construction and mega infrastructure construction management and their distinct properties.

2.3.1 The Concepts of System and Systematicness

Since ancient times, based on practical production, engineering, and social activities, humans have been focused on adopting an overall view toward the world that allows them to see the connections among all things. This has given rise to basic ideas of the world such as ancient China's harmony between nature and man and ancient Greece's perspective of an atomic world (Qian 1981), which actually reflect the unclear state of overall understanding of the world by the ancient people. This type of cognition is also a simple systematic thinking.

Since the seventeenth century, philosophers and scientists in Europe have been proposing theories about the universe. For example, Newton suggested that the universe is an interconnected system, while Leibniz proposed that everything exists in a system and its relation with the system decides what it is. The German philosopher Kant was the first to advance a theory of the systematicness of human knowledge (Qian 2011).

Scientific conceptions of systems have gradually formed since the nineteenth century, among which the most representative is one emphasized by Austrian research biologist L.V. Bertalanffy (1951, 1968) that claims that organisms should be treated as a natural unified whole, which is limited in time and space and complicated in structure. Bertalanffy defined a system as *a complex structure with interrelated multiple elements*.

Generalized and condensed from an overall perspective, the word "system" as an abstract concept for the essential property concerning the objective world and human activities is applied. That is, a system, as the most basic and important concept, reflects and generalizes the facts and characteristics of the universal connection and integrity of material objects. *The so-called system is a holistic entity that possesses certain functions and consists of interconnected, interactive, and reciprocal components*. Systems defined as this exist universally in this objective world. To be specific, a system, as a whole, is composed of multiple elements (individuals) that have various types of relations with each other and form the overall structure and holistic conduct, property, and function of the system. As such, the conduct, property, and function of a system are generally dynamic. Furthermore, a system has broad and diversified forms of interactions and interrelations with the surroundings, whereas system science is the study of relationships between the parts and the whole and the local, global, and hierarchical relations of things in the objective world from the perspective of a system.

The three basic concepts of a system involve the system environment, system structure, and system function (Bertalanffy 1975, 1981). The system environment refers to that which is external, whereas the system structure denotes that which is inside the system. One of the most important characteristics of a system is that its properties and functions, the integrity of the system, are beyond that of the components such that the external manifestation is the system structure. This means that knowing every component within the system does not equate to knowing the whole system because the integrity of the system does not consist only of the properties of its components but rather results from the emergence of the system as a whole. System research suggests, "It is a system principle of great significance that system structure and system environment as well as their relations determine the integrity and function of a system" (Yu 2014).

"According to the above system principle, to realize bringing systems the functions we expect, especially those best functions, we can manifest changes and adjustments to the structure, environment of the system or their relationships. However, we are unable to determine whether the system environment can be changed or not. If it cannot be changed, active adaptations should be made. Nevertheless, the structure of the system can be changed, adjusted, designed and organized through change and adjustment of system components or the relationships among system components and hierarchical structures and between the system and the environment to achieve coordination and collaboration. Optimal functions can be realized from the integrity of the system, which is the basic connotation of system organization and management, system control and system intervention" (Yu 2014).

Summarizing the above series of statements and definitions of a system, it is evident that a system, in a universal sense, has its own inherent and unique characteristics (properties) as follows:

1. Diversity (every system is composed of multiple elements)
2. Correlation (the varied elements of a system are correlated)
3. Integrity (the existence, behavior, function, etc. of a system are coherent with each other)
4. Dynamic (the state and behavior characteristics, etc. of a system are in flux)

These properties, i.e., diversity, correlation, integrity, and dynamics, are generally referred to as systematicness. The integrity of a system is perceived as the most important property given that the other properties contribute to and are a part of the system's integrity.

Systematicness, and integrity in particular, has profoundly changed the way we think and solve problems, which is manifested as follows:

1. In many cases, the object being studied should be treated as a whole to analyze its structure and function and examine the relationship among the whole, the essential elements, and the environment.
2. In addition to adopting the traditional research methods, such as analysis, decomposition, and anatomy, there should be a focus on the study of the correlation, the integrity of the problem, and the connection with the external environment.

The concepts of system and systematicness and the change in thoughts to which the concepts give rise are of great significance as we seek to understand construction and construction management, and furthermore, they have important instructive meaning with respect to their properties.

2.3.2 Systematicness of Construction and Construction Management

The substantive characteristics (properties) of construction and its management are examined according to system science thought, especially the definition of system.

Every construction entity is a holistic item composed of correlations and a combination of a variety of material resources, e.g., land, capital, material, equipment, etc., under the control of the laws of nature and technology. Owing to the fact that a construction has an explicit physical hard structure that forms the basic physical functions and that these material resources are essential elements for the physical engineering of the overall construction (Williams and Samset 2010), any construction, from an overall level, appears as a complete form of an entity system, which means that *any construction is a system*. A construction entity system is generally considered a construction *hard system* that forms a new *construction-environment composite system* by combining with the surrounding social and economic environment after the completion of the construction.

Because the core of the construction practice is creation, it is a process of overall activity during which hard resources are successfully integrated into the construction's hard system by the formation, design, and implementation of construction ideas. Thus, *any practice of construction is the practice of the system*.

Meanwhile, any construction practice also constitutes a complete orderly activity based on a variety of practical elements. This overall activity includes the functions of each aspect of the practice, the relations among the practices, the order and interface, and the final systematically integrated modality of practice (Williams 1999; Winch 2013). In other words, construction practice fully reflects the basic properties and characteristics of the system such that *every construction practice is the practice of the system*.

In the same way, any construction management activity is composed of elements of basic management activities. Furthermore, various management activities are related to each other in light of certain rules and principles that reflect the function and behavior of the management activities. In this sense, the construction management activity is a type of system that serves the design and construction of a hard system. Therefore, to distinguish it from a construction hard system, we refer to the construction management system as a *construction soft system*.

Similarly, *any construction management practice is not only the practice of the system but also the system of the practice*.

Based on the concept of system, the following pivotal understandings of construction and construction management have been derived: *any construction and construction management practice is the practice of the system and the system of the practice*.

Therefore, *systematicness is assumed to be the substantive property of construction and construction management*.

What constitutes the systematicness of construction management? To answer this question, we first consider the connotation of construction and the definition of system given that people are naturally involved when considering how to examine the construction and management of the activities of construction creation from a systematic perspective. Specifically, this process includes the following two aspects:

1. Examine construction with the system. Understanding, analyzing, and solving problems that involve the management of project construction organization

considering the principle and method of the system are substantially consistent with the concepts that construction is the activity of creation through the orderly integration of resources, that construction resources are generally the elements of a hard system of construction, and that the orderly integration of construction resources is the association and structure of the formation of the construction system. A systematic review of construction involves considering the construction to be a complete system. Additionally, through the analyses of elements, correlations, functions, and organizational behaviors, an overall plan, design, and organization of the practice of construction creation will be achieved.

2. Examine the system with engineering. This involves the adaptation of a modern engineering methodology to build artificial systems, especially those engineering entity systems composed of hard resources, such as bridges, airports, dams, ports, and other mega infrastructure constructions, as these cannot be designed and constructed only through simple experience and extensive methods but rather must be based on the principles of engineering techniques that require rigorous proof and procedure. Moreover, they require the adoption of sophisticated and integrated techniques for analysis, prediction, experimentation, etc. to create a related artificial engineering system that is both scientific and reliable.

In the middle of the twentieth century, the system techniques of analyzing, planning, organizing, and managing based on the principles of systems were named as systems engineering. Accordingly, construction management is, in essence, systems engineering within the field of engineering creation, and thus, it can be referred to as the *construction of systems engineering*. With respect to general engineering, the management, i.e., construction of systems engineering, is largely concerned with the planning, designing, and operating of the engineering according to the concept of system. It further includes clear goals, a rigorous analysis, an emphasis on sequencing and on a quantitative method to obtain coordination between the engineering and the environment, and a focus on the continued maintenance of good comprehensive functions of the engineering within its lifetime as well as the gradual expansion to comprehensive functions that span issues related to the engineering, society, economy, environment, etc. (Koontz and Weihriclh 1988; Zhang 2009).

The application of systems engineering first began with the hard systems of engineering, and its greatest success was actualized through the application of the organization management of the hard system of engineering, which presents a "rigid" structure owing to the definite correlation among certain elements. The properties of this type of system, to a large extent, can help us understand and analyze the overall quality of engineering. At the same time, the structural model and optimized method can help us to find the optimal program for the engineering.

Thus, the systematicness of construction management is summarized as follows. The premise of construction management is the plan, design, and on-site operation of construction creation activities that are conducted based on the concept of system. However, this premise of construction management consists of a clear goal and a rigorous analysis, and it emphasizes sequencing and a quantitative method to achieve the overall objective and comprehensive effect of the construction. More generally, *the systematicness of engineering management includes adhering to the unity of integrity and correlation and involves the dynamics of the activities with respect to the engineering creation process in management*.

The above understandings of construction and its management based on system properties are of great significance because they promote cognition from the intuitive and perceptual perspectives to the theoretical perspective concerning their substantive properties. As such, the epistemology based on the abstraction of the system can be established beyond the concreteness of construction and its management, and thus, a further description of the basic definition and relative theories of construction and construction management can be provided by applying logic and discourse systems of the scientific thinking system. This will provide a thinking paradigm and guidelines that will enhance further understanding of mega infrastructure construction and mega infrastructure construction management.

2.3.3 The Concepts of Complex Systems and Complexity

As human society develops and its degree of organization improves, the essential elements that constitute the system are increasing, the types of connections among these elements are growing more complex, and the formation path and change patterns of the overall performance of the system become increasingly more diversified. In this way, on the basis of the original concept of system, people have a perceptual intuition of a complex system, i.e., a system that is complex. However, referring to a system as complex may suggest that the system is composed of many elements with different properties and that the connections among those elements may vary. This indicates that the complexity of a system is the result of its own noumenon or phenomenon. Another cause of such complexity could be that the cognitive subject fails to fully comprehend and understand the internal structure and correlation of the system, that is, the subject exhibits a deficiency in cognitive ability or the deficiency is caused by the ontology and subjective cognition of system (Anderson 1972; Ladyman et al. 2013). Of course, claiming that a system is a complex system, as we usually do, often begins with a subjective perceptual cognition. For example, being unclear about the essential elements of which the system is comprised, not knowing how these elements are correlated, being unable to fully comprehend the behaviors, phenomena, and changing trends of the system, etc. all contribute to and shape intuition and feelings.

On the basis of analyzing and summarizing the characteristics of a large number of complex systems, the scientific concept of a complex system has been gradually formed in the field of system science. This is a scientific concept in the field of system science that is formed by the abstraction of one type of the system's own properties. Though the two expressions appear quite similar, they are not exactly the same. At present, the basic meaning of the concept of complex system is as follows:

For one category of system, if its elements possess the properties of heterogeneity and self-adaptability and if its structure is hierarchical and its overall behavior and function cannot be simply formed by adding each aspect of its behaviors and functions together, it can be considered a complex system.

Thus, a complex system is a type of system that is unique within the category of system, and *this property of a complex system is referred to as complexity*.

Thus, how do we depict complexity?

First, as a property of complex systems, complexity is a scientific term derived from the everyday word "complex." Complexity, whether it be at the epistemological or the ontological level, is defined separately. Although, in general, the complexity of things is related to both the subjective cognition and the objective connotation, herein, complexity is perceived according to its ontological properties (Chen and Liu 2014; Simon 1991).

According to their own research questions and the phenomena of different disciplines, such as physics, chemistry, and biology, different descriptions and definitions of the scientific term complexity have been provided, which leads to diversified definitions of the word and reflects the normal phenomenon of the differences in the connotations of varied disciplines.

After abstracting the essential properties of a large number of complex systems, and especially after considering the requirements of mega construction management research, we summarize the major sources and manifestations of complexity that place special emphasis on the background of mega construction:

1. There is a high degree of openness and interaction between the system and the environment. The environment is dynamic, uncertain, and evolving, and as such, it is a closely related and interactive system.
2. A large number of elements, which have characteristics of heterogeneity and adaptability, constitute a system. This means that there exist relatively great differences among the aspects of properties, effects, and functions of elements and that these aspects can actively adjust their own states and behaviors according to the information received to adapt to the changes in the environment and be more beneficial to their survival and development. Simultaneously, new rules will be generated, and new conditions will be formed from the system so that the system will possess overall behaviors and functions that are more advanced and more orderly.
3. Systems generally harbor complex overall behaviors and functions that do not exist in single elements of the system. Such behaviors and functions are not formed simply by adding those of single elements of the system together but rather can only be achieved at higher or overall levels. This phenomenon is referred to as *the emergence of system behavior and function*. Emergence is one of the important characteristics of complexity (Rocha 1999; Reuven and Shlomo 2010).

Complexity exerts profound changes in the way we perceive problems and in the way we solve problems. These changes are manifested as follows:

1. The complexity of a system is based on the complexity of the elements of the system and the correlated structure. Therefore, decomposition and an understanding from the top to the bottom of system properties, an understanding of the partial structure, and an analysis and control of meso and micro behaviors in an overall sense are essential.
2. The complexity of complex systems is often the result of the emergence of the complex behaviors of system elements themselves and the complex relations among those elements. Therefore, meso and micro parts should be put together to prove a better understanding of the overall system complexity at the macro level. According to the two aforementioned points, (1) is considered the reduction method and (2) represents the holistic approach. In addition, a combination of the two methods should be applied when addressing problems regarding complex systems.

2.3.4 Complexity of Mega Infrastructure Construction and Its Management

A complex system and the concept of complexity are of great importance when seeking to understand the essential properties of mega infrastructure construction and its management.

2.3.4.1 The Complexity of Mega Infrastructure Construction

A summary of the basic characteristics of mega infrastructure construction is provided in Sect. 1.2.2. Based on a discourse of system science, if a further application of system analysis was performed to analyze, systematically, mega infrastructure construction, it would reveal that mega construction has the following characteristics:

- The construction environment of mega infrastructure construction is dynamic and open
- The main body of mega infrastructure construction is multidimensional, heterogeneous, generally autonomous, and adaptable
- The essential components of mega infrastructure construction are highly connected, and their interactions are presented in various complex states
- The process of mega infrastructure construction is the combination of system organization and self-organization.

Comparing the features of mega infrastructure construction with the basic concept of a complex system, as described in Sect. 2.3.3, it can be concluded that mega infrastructure construction is actually a complex system or a complex construction system. In other words, *mega infrastructure construction can be safely considered* *to be a type of an artificial complex system*, and the construction physical entity to which it refers is *the hard system of a complex system*.

Because mega infrastructure construction is a type of complex system, it naturally possesses the complexity of complex systems, as previously described herein.

Not only is the mega infrastructure construction, one type of complex artificial system, a type of complex system that embraces the property of complexity but so is the mega infrastructure construction-environment compound system, which combines mega infrastructure construction with the surrounding socioeconomic and natural environments.

Consequently, how to accurately and fully depict the conclusion that mega infrastructure construction is a type of complex system and that it encompasses complexity is a problem that must be addressed. The first consideration lies in the principle of human cognition, which evolves from the concrete to the abstract and from the perceptual to the rational. As a result, human beings would initially perceptually notice the physical complexity of the mega infrastructure construction, such as the physical complexity of the tangible construction, as the mega infrastructure construction is large in scale and the construction entity is complex in technique and environment. In other words, it comprises the most perceptual and direct knowledge of mega infrastructure construction from the level of a mega infrastructure construction hard system that is composed of hard resources. Next, people conceptualize the physical complexity of a mega infrastructure construction hard system based on scientific preconceptions of a system, and thus, they express, through discourse, a system science to extract the essential properties of a complex mega infrastructure construction system, such as a highly open environment, a heterogeneous entity, close connections among components, multiple constraints, and the evolvement and emergence of a construction system's behaviors and functions (Ledford 2015). According to this, the complexity of a mega infrastructure construction is the reflection and abstraction of its physical complexity within the category of a complex system, and thus, it represents the reflex of the complexity of the mega infrastructure construction physical form in complex system space.

2.3.4.2 The Complexity of Mega Infrastructure Construction Management

Because mega infrastructure construction is a type of artificial complex system with the characteristic of complexity, it is destined to encounter a complex management problem during its management activities. Accordingly, the mega infrastructure construction management problems could generally be categorized based on both of the complex degrees of the construction itself or on the construction environment. As displayed in Fig. 2.2, because the level of construction and the environmental complexity of the problems within region A (hereinafter referred to as Type A) are relatively low, they are comparatively simple problems that generally can be solved through mature experience and knowledge. With respect to Type B, obvious uncertainty and dynamic relations will present in management problems owing to the

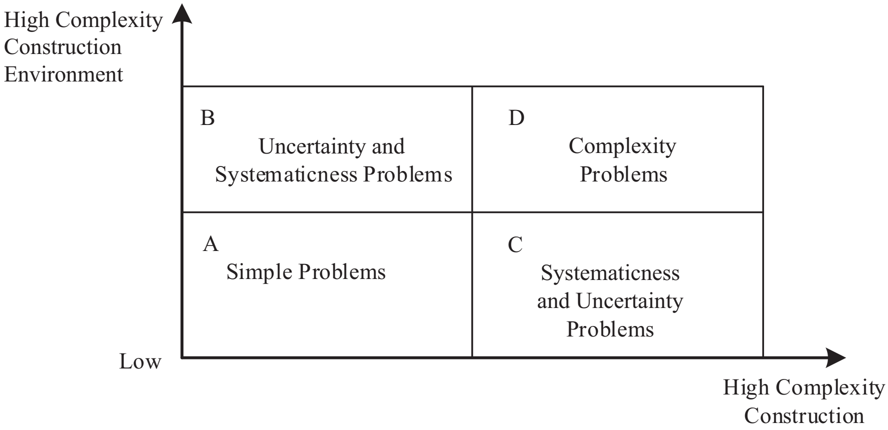

Fig. 2.2 Mega infrastructure construction management problem categorizations

high level of environmental complexity, and due to the high degree of construction complexity of Type B, the inner structure of the construction is complex. Even if the construction environment is relatively simple, problems of definite uncertainty and unsteadiness may occur. Furthermore, because of the highly connected inner elements of the construction, implicit conduction and evolution of the mutual influence among elements could easily occur. Accordingly, management problems that fall into Types B and C could generally be solved by formulating management rules, improving regular conditions, and making use of mature experience and knowledge. Moreover, the problems that present systematicness can be solved with system construction techniques. This illustrates that many of the mega infrastructure construction (Types A, B, and C) management problems can be resolved through the combination of scientific management and systematic management of mega infrastructure construction.

With respect to Type D, these are types of complexity problems resulting from the high complexity of both the construction and the environment that must be solved regularly and efficiently by following systematic complexity management thought. Such problems include the design of a heterogeneous organization management platform, an iterative pattern generating method for highly uncertain project decision-making and its plan, mega infrastructure construction risk analysis and management, multi-subject coordination in a construction site, multi-objective comprehensive control, the innovation of key construction techniques, etc.

According to the above analysis, it is concluded that mega infrastructure construction problems can be categorized into three levels (see Sect. 2.3). Combining the second level of Fig. 2.3, which incorporates problems of Types A, B, and C, with the top level of Type D, a complete system of mega infrastructure construction management problems is formed (see Fig. 2.3).

It is generally considered that the mega infrastructure construction problem system categorizes the problems into complex management problems, relatively com-

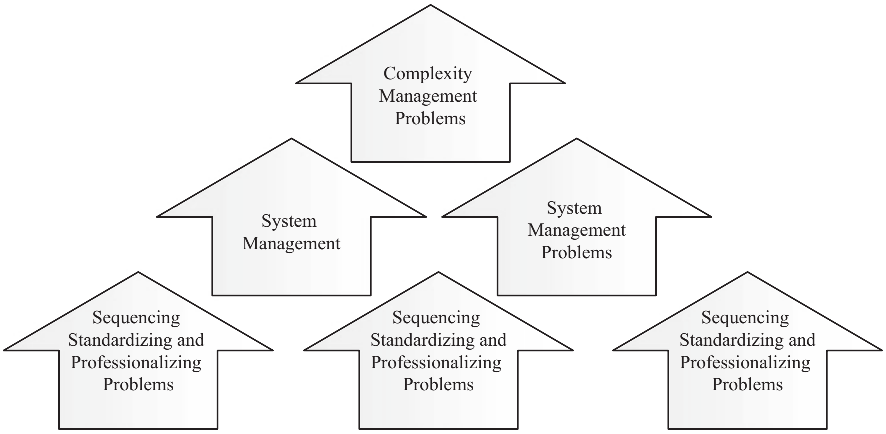

Fig. 2.3 Mega infrastructure construction management problem system

plex problems, and relatively simple problems. Based on such categorization, there certainly exist objective reasons related to physical and systematic attributes of the problems themselves; however, it also has much to do with the cognitive ability of the management subject. Because of this, it cannot be concluded that a rigid and sole problem system structure absolutely exists in any mega infrastructure construction. Rather, it is acknowledged that mega infrastructure construction is, to some extent, soft and dynamic. For instance, if two management subjects are unequal in ability, the one with the greater ability will conclude that there are fewer management problems, while the one with a lesser degree of ability will not agree. Even if only one management subject is included, that individual will consider that the complex problems at the top will decrease and the level of complexity will decrease with the increase of mega infrastructure construction information and the promotion of the subject's cognition. The mega infrastructure construction cognition of those management subjects who are highly professional and who have a wealth of experience will suppose there are rarely any management problems, which means that, for them, there are only two levels of problems rather than three.

Furthermore, since mega infrastructure construction management is a systematic practice whose major task is to solve complex management problems, it must include the three functions, namely, recognition, coordination, and conduction, of complex management problems. Thus, the basic structure of a mega infrastructure construction management system is generally composed of the following three subsystems:

1. A recognition system of mega infrastructure construction management whose main function is to uncover and analyze the construction complexity and systematic complexity of mega infrastructure construction, according to which the complexity of the mega infrastructure construction management problems will be analyzed.

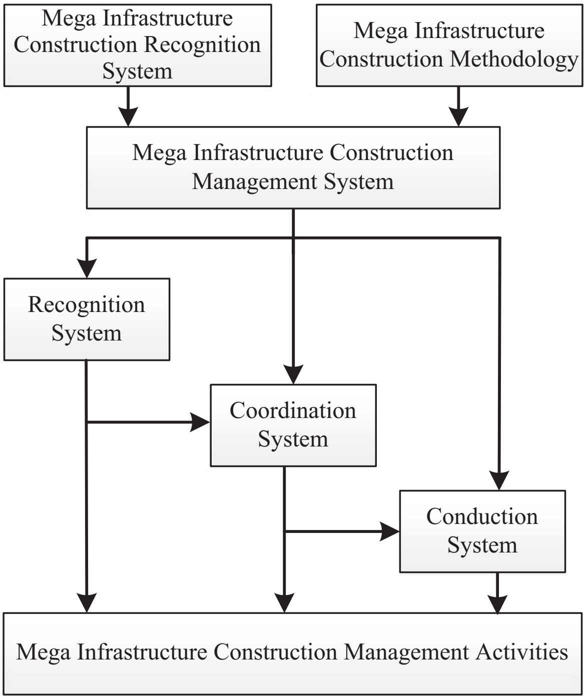

Fig. 2.4 Basic structure of mega infrastructure construction management activity

2. A coordination system of mega infrastructure construction management whose primary functions are the designing and degrading of the complexity of management problems through the operation mechanism and process of management organization and the conducting of a series of unique management strategies of adaptability and multi-scale management.
3. A conduction system of mega infrastructure construction management whose major function is to conduct multi-subject coordination and comprehensive control of the construction site at every stage and level of management according to the management objectives and the strategies of the coordination system (see Fig. 2.4).

To summarize, mega infrastructure construction management activities whose major tasks are to analyze and solve complex problems during the process of mega infrastructure construction creation, similar to mega infrastructure construction, belong to a specific type of complex system, i.e., the *mega* infrastructure *construction soft system*, and possess the essential attributes of complexity.

Accordingly, *the process from construction management to mega infrastructure construction management forms the evolutionary principle from systematicness to complexity*. The core of this conclusion is that mega infrastructure construction management is a type of complex system (Flyvbjerg et al. 2003; Lehrer and Laidley 2008). The major functions of mega infrastructure construction activities are as follows:

1. To well organize and manage self-learning and self-adaptation behavior of the subject and coordinate work
2. To establish a model of construction organization that includes the evolution of self-organization, the self-adaptability of organizational elements, structure, and function; and the dynamic change of the construction environment and tasks
3. To continuously condense and synthesize the objectives of mega infrastructure construction
4. To form management solutions through the process of comparison, trial and error, iteration, and approximation

In this way, *mega* infrastructure *construction management activities maintain and manage the complexity of mega* infrastructure *construction management problems through the self-adaptability and self-organization of the management subject*.

In the domain of system science, the process from systematicness to complexity does not involve an increase in the quantity of systematicness but rather an increase in the quality, which leads to a series of significant differences in the management thinking, principles, and methodologies of both construction management and mega infrastructure construction management. Therefore, general systematic methods of construction management cannot be simply applied to mega infrastructure construction management or solve complex problems in the problem system of mega infrastructure construction management.

Furthermore, mega infrastructure construction management problems not only embrace general systematicness but also complexity, which does not translate to more systematicness. Rather, it is based on the quality of the change of systematicness and its increased complexity after its evolution.

In this sense, complexity becomes the fixed property of mega infrastructure construction management problems. *Since mega* infrastructure *construction management activities are the integration of hard system and soft system mega infrastructure construction, the complexity is naturally the combination of the complexity of both the hard and soft systems*.

More generally, the process from systematicness to complexity is the change of essential properties from construction management to mega infrastructure construction management. This conclusion harbors essential fundamental meanings for setting theoretical thinking principles and constructing theoretical systems of mega infrastructure construction management.

2.3.4.3 Complex Integrity of Mega Infrastructure Construction Management

Although the discourse system of system science has found that complexity is the essential property of mega infrastructure construction management, further analysis should be conducted on the deeper connotation of this property, thereby combining the characteristics of mega infrastructure construction creation activities.

Any mega infrastructure construction aims primarily to achieve a complete artificial complex system through design and planning. Given this circumstance, integrity is the foundation of mega infrastructure construction creation and management activities, including the physical and functional forms of the construction system and the complete system and process of related management activities. In other words, all construction creation and management activities must be complete and reliable to realize the creation of an artificial construction system.

This means that with the goal being human creation, not only must the construction hard system that integrates construction hard resources be a complete whole but also the mega infrastructure construction management activities, which combine their hard and soft systems and ensure the order and efficiency of mega infrastructure construction creation activities, must be a complete whole (Altshuler et al. 2003; Yu and Liu 2002). Otherwise, a complete artificial construction hard system cannot be realized.

Moreover, from the perspective of theoretical logics, both general and complex systems are characterized by the property of integrity. The problem lies in that, from construction management to mega infrastructure construction management, significant essential change from systematicness to complexity occurs, resulting in great changes in performance and in the methods applied to realize integrity.

More specifically, the integrity of construction and its management activities can be degraded by reductionism and be achieved through the composition of every subactivity (Plotch 2015).

For instance, with respect to construction management activities, management objectives are embodied in the direct, noticeable, and physical level of the project such that the objectives of integrity management can be reduced to the management objectives of every part of the project and be realized by the superposition of relatively simple methods.

However, for mega infrastructure construction and its management activities, integrity cannot be achieved through such simple theories of reductionism and superposition. For example, the management objectives of mega infrastructure construction management activities involve not only those at the direct, noticeable, physical levels but also those at the indirect, unnoticeable, socioeconomic levels and involve not only those of the same dimension and scale but also those of different dimensions and scales. Some of the objectives even emerge from the mega infrastructure construction-environment compound system. Under this circumstance, it is extremely difficult to realize the integrity of management objectives through the simple theories of reduction and superposition. This indicates that a type of complex integrity that appears in mega infrastructure construction management activities not only manifests itself in the overall design of management objectives but also is reflected by many other management problems as the manifestation of the complexity of mega infrastructure construction management activities (Flyvbjerg 2003).

Therefore, although integrity is the common quality of general and mega infrastructure construction, the former embraces the superposition of integrity in general systems, which is called *general integrity*, and the latter encompasses the nonsuperposition of integrity in complex systems, which is referred to as *complex* *integrity*. In this way, when a mega infrastructure construction management system combines a construction hard system with a soft system to form the whole of an activity, the complexity of the mega infrastructure construction complex hard system (management target system) and complex soft system (management subject system) is combined to create the complex integrity of the mega infrastructure construction management activities.

In this sense, it is considered that mega infrastructure construction creation and complex integrity are the pivotal origins and deep connotation of the complexity of the mega infrastructure construction management activities. Therefore, within the mega infrastructure construction management activities, the thoughts based on the analysis and problem solving of complex integrity and the methods to research complex integrity problems must be established (this will be covered in Chaps. 4 and 8).

2.4 System Structure and Cognition of Mega Infrastructure Construction Management

The contents covered in the first part of this chapter are fundamental and essential to this book because the early sections summarize the perception of mega infrastructure construction management activities and present abstractions of scientific connotations and condensations of essential attributes of mega infrastructure construction management based on the introduction of the fundamental theories of system science. Thus, because the groundwork has been laid, the overall knowledge of mega infrastructure construction management can be realized under the premise of system science, and thus, the cognitive paradigm, with respect to the subject, organization, and activities, of mega infrastructure construction management, which constitutes the essential knowledge of mega infrastructure construction management, can be formed. This is the fundamental early stage for building the system of mega infrastructure construction management.

The cognitive paradigm is the comprehensive, accurate, and standardized understanding of the essential attributes of entities given certain principles of theoretical thinking. Only with the profound, comprehensive and accurate understanding of mega infrastructure construction management can a scientific and appropriate method of researching its problems, especially the related theoretical research, be found.

First, it should be noted that any mega infrastructure construction management activities and their corresponding construction creation activities are generally synchronous, which means that at the beginning of a construction creation activity, the related management activities begin, and once the construction activity terminates, the related management activities end. However, as human construction activities grow increasingly complex, the corresponding construction management activities tend to advance to forming construction management thoughts and conducting early-stage construction decision-making, planning, and argumentation and then proceed to the operation and post-evaluation periods of the construction. Thus, the overall process of construction management, at least the management activities in the early stage of construction decision-making and in the stage of actual construction, should be included in the cognition of mega infrastructure construction management. If possible, operations after the construction should be involved because the comprehensive management of mega infrastructure construction, including decision-making, construction, and operation, has received increased emphasis in modern mega infrastructure construction.

Based on the above thinking, this section presents an overall cognition of the entire process of construction management with respect to the early-stage construction management activities.

2.4.1 Mega Infrastructure Construction Decision-Making Subject and Integrated Decision-Making Support System

There are reasons for developing mega infrastructure construction. For example, a bridge is built to improve traffic conditions, whereas a dam is constructed to prevent floods or generate power. When it is decided that there is a need for a mega infrastructure construction project, a group of people, possibly those who conceived of the idea or people who have been entrusted by others, must research the concept and determine at the macro level whether the mega infrastructure construction can and should be undertaken, where, when, and how to implement the project, etc. This constitutes the beginning of the mega infrastructure construction early-stage decision-making, and this assemblage of people forms the decision-making group. As such, they are commonly referred to as the *mega infrastructure construction decision-making subjects*.

The main task and function of the decision-making subject involve a series of significant tasks from a macro and holistic sense, such as clarifying and designing the general plan for the mega infrastructure construction and approving and defending the related projects, the purpose for the construction, and the plan design. Accordingly, the decision-making subjects of a mega infrastructure construction must possess the administrative rights and powers to make decisions and resolve problems. As such, the government or its agents, who are entrusted by the public, generally possess such rights.

Because every mega infrastructure construction creation is a highly complex, albeit practical, activity, the decision-making subjects must embrace the ability to make appropriate scientific decisions regarding major problems, which means that, in addition to the necessary administrative rights and power, the subjects must harbor the requisite high levels of wisdom, knowledge, and ability. Possessing the administrative rights without the necessary intelligence can result in incorrect decisions and mistakes.

However, in reality, everyone has limited individual intellectual levels, while the number of decision-making problems in mega infrastructure construction is substantial and the problems are too complex, as they are often across-levels, multidisciplinary and interdisciplinary. Therefore, they cannot be solved by an individual or even a group of subjects from a single area; rather, such problems require an expert system that includes scientists from different fields and disciplines and experts from various relevant areas who possess the requisite knowledge and wisdom.

Therefore, mega infrastructure construction decision-making subjects should have an integrated decision-making support system composed of a group of experts who are familiar with all types of decision-making problems and can provide the necessary decision-making support during the decision-making process.

The overall decision-making support system should possess the following characteristics:

1. The main functions of this system are to employ an overall plan, demonstration, and design concerning over significant decision-making problems in mega infrastructure construction, to conduct an overall analysis of complex problems related to the physical structure and function of the construction and the relationship between the construction and the environment, to create an overall scheme that addresses all types of decision-making problems through various means and methods, and to offer those schemes to the decision-making subjects as a scientific basis and reference for decision-making.
2. Based on being multidisciplinary and across fields, this system applies qualitative and quantitative means and approaches, such as analysis, experimentation, modeling, simulation, evaluation, and optimization, as well as scientific experiments, as part of the decision-making process. To achieve this, a strategy that combines humans with computers while emphasizing the former must be adopted by the department to realize the comprehensive integration between data and information, knowledge and wisdom, scientific theory and practical knowledge, qualitative and quantitative knowledge, and rational and perceptual cognition of varied disciplines and fields. This strategy, through the interactions between humans and computers, the repeated comparisons, and the gradual approximations, can help to actualize cognition from qualitative to quantitative and draw scientific conclusions about whether the empirical hypotheses regarding the decision-making problems are correct.
3. This system primarily addresses issues related to the research and analysis of major project constructions, including physical structure, function, site selection, technique plans, and economic benefits of the project as well as the co-relationship between the project and the environment. However, a great amount of resources, such as labor, money, materials, information, and knowledge, must be invested into any type of major project construction. Consequently, it is necessary to research and analyze how to integrate and configure these resources and how to complete high-quality construction tasks at relatively low cost within a short period of time. To accomplish this, the system must conduct an overall plan and demonstration of the major project construction's hard and soft systems, which include the management structure, mechanism, process, and plan. This system must not only handle

the hard and soft systems of major project constructions separately but also connect and combine them to form a new complete system that will conduct the overall planning, certification, and design of a construction project.

4. If administrative rights and powers are the major resources for decision-making subjects, the major resource for an overall decision-making system is the group of experts from various fields who possess decision-making wisdom generated by the comprehensive integrated method system. The former ensures the authority for the mega infrastructure construction, whereas the latter guarantees the scientific legitimacy of the decision-making schemes.

2.4.2 Mega Infrastructure Construction Management Integrated Execution System

Supported by an integrated decision-making support system, decision-making subjects have access to a complete series of decision-making schemes for mega infrastructure construction creation and management through the evaluation, demonstration, and optimization of all types of contingency plans that may be implemented via an *integrated execution system* (department). During this process, plans regarding the construction structure, function, techniques, etc. formed by the decision-making subjects evolve into an intact construction entity with the help of the construction creation subjects, i.e., contractors and suppliers, who are organized via the integrated execution system. The ultimate form of the construction management system, mechanisms, strategic plans, coordination methods, etc. are developed to conform to the practical management activities of the mega infrastructure construction creation through the integrated execution system or its agents. If it is the latter, the mega infrastructure construction management system is considered to be a soft system, whereas if it is the former, the mega infrastructure construction management object is considered to be a hard system. Thus, the management activities of the mega infrastructure construction are formed by the integration and coupling of the two.

Therefore, the function of the mega infrastructure construction integrated execution system is to put into practice a series of integrated decision-making schemes as determined by the decision-making subjects. Although an integrated execution system may be deeply involved in the formation of a mega infrastructure construction hard system, its major function is to organize and manage the formation of the mega infrastructure construction hard system as related to the construction techniques and the construction tasks that are the responsibility of the construction contractors.

Generally, because the mega infrastructure construction decision-making tasks focus on the prophase of the mega infrastructure construction with relatively short-time periods and tasks at the macro level, the tasks are poorly understood and often go unnoticed. Management activities whose integrated execution systems last for comparatively long periods of time during the process of construction, or those mainly focused on the middle and basic levels, can be misunderstood as mega infrastructure construction management activities.

In fact, the function of the mega infrastructure construction prophase decision-making system and the integrated decision-making support system is an essential aspect of the mega infrastructure construction management activities not only because decision-making remains one of the more important management activities in the field of management science but also because, in practice, the continuous tracing instruction and conduction support for each significant construction task will be provided by mega infrastructure construction decision-making subjects and an integrated decision-making support system within a rather long construction time period. In this way, from the perspective of the entire process of the construction of the mega infrastructure construction, the decision-making subjects, the integrated decision-making system, and all of its activities should be involved in the mega infrastructure construction management activities, and thus, as a whole, it is referred to as a *mega* infrastructure *construction integrated management activity*. The management activities of the decision-making subjects and the integrated decision-making system are *mega infrastructure construction decision-making management activities*, while those of the integrated execution system are considered *mega infrastructure construction management activities*.

To summarize, a flowchart of the constituent parts of the mega infrastructure construction integrated management activities is presented in Fig. 2.5.

Notes: The chart illustrates the mega infrastructure construction management activities; management activities within the construction period of mega infrastructure construction are indicated in the dashed line frame.

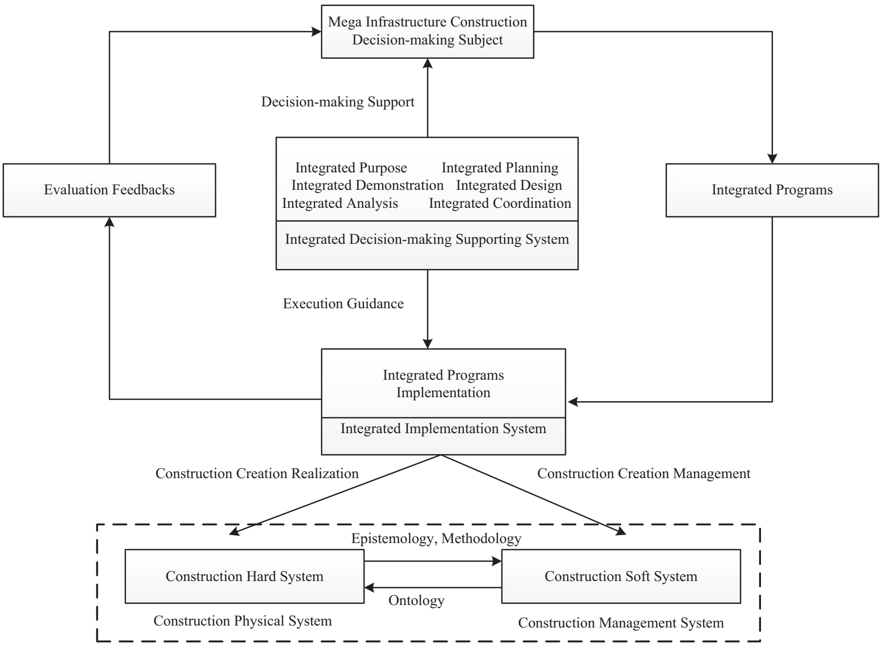

Fig. 2.5 Mega infrastructure construction management activity structure

2.4.3 Basic Paradigm of Mega Infrastructure Construction Cognition

The basic paradigm of mega infrastructure construction cognition is as follows:

1. Mega infrastructure construction activities of the management subjects and organization consist of three parts, namely, the decision-making process, the integrated decision-making support system, and the integrated execution system, each of which is composed of different subjects, has its separate organizational operations and fundamental functions, and is essentially a complex self-adaptive system in itself. The three parts correlate and combine with each other to form a more *complex mega* infrastructure *construction hierarchical distributive management organization system*, which becomes a system of complex systems? i.e., a system of complex systems, with additional complex systems as its subsystems.
2. Through the interaction of the two parts, i.e., the decision-making subjects and the integrated decision-making support system, integrative and strategic decision-making tasks will be addressed, and an entire mega infrastructure construction decision-making scheme will be formed. This scheme will be divided into two parts. One involves the physical structure, functions, conduction techniques, etc. with respect to the construction and determines the systematic form of the complete model of the construction entity, i.e., the mega infrastructure construction hard system. The other includes the concepts, theories, methods, and technical routes of construction management and, as such, determines the systematic form of the behaviors of management subjects during the formation of the construction entity, i.e., the mega infrastructure construction soft system.
3. The integrated execution system conducts a series of schemes related to the creation and management of the mega infrastructure construction, within which the main function of the management subjects is to exert overall coordination, control, and resource allocation optimization of the construction hard system and soft system to ensure the realization of the integrated purpose of the mega infrastructure construction with order and efficiency.
4. In a narrow sense, the activities with respect to coordination and control conducted by an integrated execution system are referred to as mega infrastructure construction management activities. In a broad sense, however, decision-making support activities by decision-making subjects and an integrated decision-making support system are also involved in mega infrastructure construction management activities that constitute the integrated mega infrastructure construction management activities. Together, the two types of activities form the integrated management activities of mega infrastructure construction.
5. Regardless of the categorization, together, every part, including the management system, i.e., construction soft system, and the management objects, i.e., construction hard system, in the mega infrastructure construction management activities forms the system of complex systems, which means that *mega infrastructure construction management is a self-adaptive complex system and its function it manifests*.

6. The self-adaptive and self-regulated functions of this system present themselves not only inside the system and within the integrated functions but also in their adaptability and conservatism toward the changes and evolution of politics, the outside natural environment, and the economic environment.
7. *In this way, the following paradigm of mega infrastructure construction management cognition is formed through the promotion of mega infrastructure construction management practice from intuitive perception to rational thinking of system science. Mega infrastructure construction management, i.e., subjects, organization, objects, and activities, is a hierarchical self-adaptive complex system, of which complex systems are the basic components. Therefore, complex thinking as related to mega infrastructure construction management must be built and must include thinking principles, theoretical thinking, methodology, method system thinking, etc. for the change and evolution of mega infrastructure construction management from system science to management science to be realized* (Fig. 2.6).

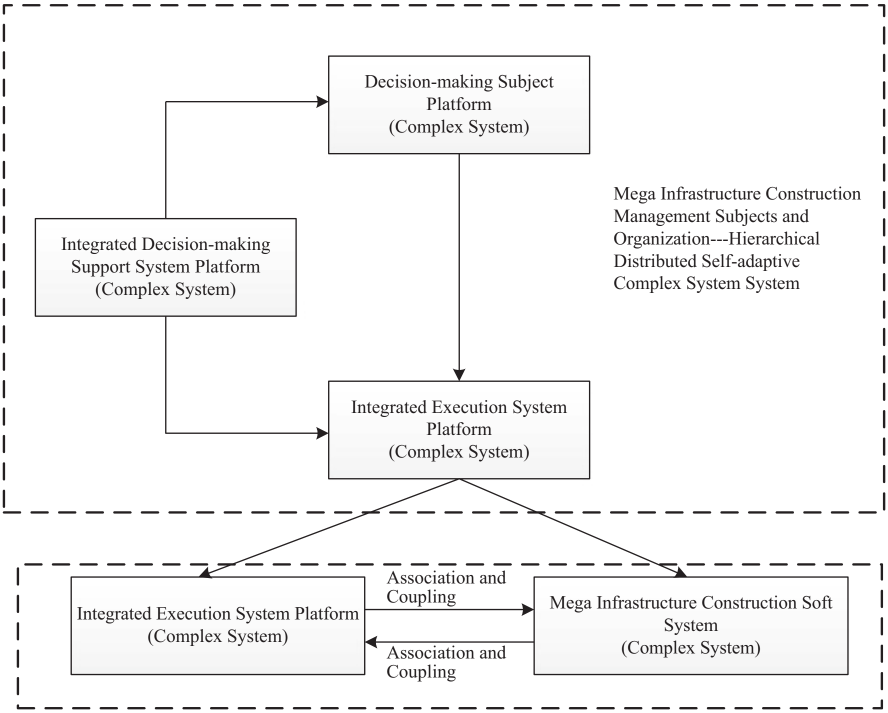

Fig. 2.6 Mega infrastructure construction management cognition based on complex thinking

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Main Themes in Part 1

Engineering is a creation practice and process based on certain intentions of human beings where a successful product of practice leads to a specific and real engineering entity.

Significant engineering is a type of large-scale, profound, and important engineering. Accordingly, mega infrastructure construction is one aspect of significant engineering that promotes long-time socioeconomic development and improves the living environment for man.

As a great power in mega infrastructure construction in the contemporary world, China has gained a wealth of experience in recent years, which contributes to the research of and thinking about mega infrastructure construction management theories.

Both engineering and its management are artificial systems whose essential property is systematicness. In this sense, any type of engineering and its management are not only the practice of a system but also the system of practice.

Both mega infrastructure construction and its management are artificial complex systems such that complexity is their essential property. Again, any type of mega infrastructure construction and its management are not only the practice of a complex system but also the complex system of practice.

Construction management is a type of activity that ensures the order and effectiveness of construction creation through resource integration and allocation, subject task distribution and arrangement, and relationship coordination among subjects, among tasks, and between subjects and tasks according to a vested purpose in the process of construction creation.

Compared with construction management, many new characteristics have appeared in and been added to mega infrastructure construction. From construction management to mega infrastructure construction, a law of evolution from systematicness to complexity is formed and becomes an essential property.

Complexity is the characteristic of the integrity of mega infrastructure construction and its management, the coupling of which forms the complex integrity of mega infrastructure construction. This contributes to the significant cause and profound connotation of the complexity of mega infrastructure construction management.

By combining these conclusions, a basic paradigm of mega infrastructure construction management cognition is formed, indicating that mega infrastructure construction management organization is composed of a decision-making subject, an integrated decision-making support system and an integrated execution system with distinct subjects constituting different parts, each of which possesses its separate organizational operation approach and basic function. Every part is essential to the complex self-adaptive system, the interactions of which compose a more complex system.

With the help of an integrated decision-making support system, the decision-making subject proposes a series of corresponding schemes regarding mega infrastructure construction creation and management during the prophase of construction. The integrated task of the management subject in the integrated execution system is to realize the orderly and effectively integrated purpose of mega infrastructure construction during the construction through the combination and coupling of the hard and soft systems and through the management activities, such as the coordination, control, and optimal resource allocation of the hard and soft systems of mega infrastructure construction.

The management subject and organization of mega infrastructure construction, the management system and activities, and the entire integrated mega infrastructure construction management constitute a type of hierarchical self-adaptive complex system.

Part II
Fundamental Considerations for Mega Infrastructure Construction Management Theories

This section, comprising two chapters, serves as a significant link between the preceding section and the following section. Two modes of thinking adopted in construction management practices are put forward, namely, theoretical thinking, which clarifies general principles of construction, and construction thinking, which turns virtual construction into entitative construction. Construction management theories are the outcome of theoretical thinking.

Accordingly, the project management knowledge system is a system of knowledge and skills that, characterized primarily by construction thinking, provides guidance for "what to do" and "how to do." Therefore, the project management knowledge system should not be perceived as being theoretical-thinking-based or as being a standard theory system of construction management, nor should it serve as a normative theory system of mega infrastructure construction management.

The design and establishment of a normative theory system of mega infrastructure construction management relies on all of our efforts, as it is an exploring process of great significance in the field of mega infrastructure construction management. Regardless of the explorer's perspective and level, this process should follow the basic rules and regulations of theory formation. Generally speaking, to establish mega infrastructure construction management theories, one must advance and refine the cognitive principles, key concepts, fundamental rationales, and scientific problems that emerge from mega infrastructure construction management practices and feature theoretical thinking to improve the gradual evolvement among these elements.

Chapter 3
Mega Infrastructure Construction Management Theories: Overview

In human history, mega infrastructure construction has dramatically transformed the appalling natural environment and improved people's living conditions and quality of life. Apart from great construction achievements, engineers and professional managers have enriched their experiences in and knowledge of mega infrastructure construction management.

Since the last century, the scale of mega infrastructure construction has grown increasingly larger, the construction environment and technologies have become increasingly more complex, and increasingly more difficult problems have emerged in every phase of mega infrastructure construction from decision-making to design, building, operation, and maintenance. Consequently, with respect to mega infrastructure construction management practices, increasingly more wrong decisions have been made, investments and expenditures have spun out of control, and safety and quality risks have increased. Thus, people feel ever more helpless when facing such management complexities.

Confronted with such challenges, in addition to enhancing their knowledge through learning, accumulating management knowledge, and drawing on lessons from past experiences, people begin to contemplate the same question with reference to the relationship between theory and practice and the guiding role of theory in practice.

Is there any mega infrastructure construction management theory based on relevant management practices, and how can such a theory be formed that would convincingly explain mega infrastructure construction management phenomena, reveal general rules, and guide management practices? Such a theory is of particular importance at a time when people are facing such varied challenges in this field.

This question is not an easy one to answer, nor can it be answered directly, because it is actually a chain weaved by a series of related questions, among which there is a logical sequence. Thus, only when the former question has been clearly answered can the subsequent one be addressed. In other words, the overarching question remains unanswered until all of the sub-questions have been sufficiently resolved.

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What, then, are the sub-questions that must be answered before we can tackle the real question, "Is there any mega infrastructure construction management theory, and how can such a theory be formed?"

1. Theory is the product of human thinking based on practices. What, then, are the major modes of thinking that people adopt in mega infrastructure construction management practices? Which mode of thinking produces mega infrastructure construction management theory?
2. Can we adopt a project management knowledge system that plays a significant role in construction management practices as a mega infrastructure construction management theory? If so, we can then claim that there is a mature mega infrastructure construction management theory.
3. If not, we must explore how to establish such a theory. What would be the theoretical principles and paradigms of such a theory?
4. How can we conduct specific explorations and experiments while creating a mega infrastructure construction management theory?

It is evident that these questions are linked together and form a logical chain of questions with respect to the building of a mega infrastructure construction management theory.

It is noted that the mega infrastructure construction management theory does not refer to certain revealing theoretic questions since such questions are, more often than not, isolated and broken. Moreover, there exists no common theoretical ground among them, and the explanations to the questions are not of the same theoretical origin. Therefore, even if there are many such theoretic questions, they may never delve deeply enough into the concept of mega infrastructure construction management to reveal its general rules and essential properties. Instead, *the theory refers to a theory system that reveals the essential properties and general rules of mega infrastructure construction management*, which, in turn, reveals the essential properties and general rules of mega infrastructure construction management.

A theory system is not a group of separate theoretical opinions that lack internal logical connection. Rather, it requires not only common principles of theoretical thinking but also conceptual systems, fundamental rationales, and scientific questions that penetrate the essence of the field. It is also imperative to recognize the need for an appropriate systematic methodology. Compared with the isolation and incompletion of separate theoretic questions, a system theory, instead, should reflect the logicality and systematicity of the theories in the field.

Given the above, building a theory system of mega infrastructure construction management is much more complicated and difficult than solving individual theoretic questions about management. Since the establishment of a theory system involves many fields, including engineering, philosophy, cognitive science, noetic science, and management science, we should never confine ourselves to the field of construction management or corresponding technologies and methods when solving certain problems. In doing so, we would fail to reach the level of thought required to form scientific opinions on the theory system, and we would be unable to determine all of the essential questions through the logical sequence of the question chain and thereby be unable to find the final answer to our question.

When discussing the phenomena of theoretical disciplines combined with engineering phenomena, the Chinese philosopher Changfu Xu once noted that the task of theoretical thinking is to build theories, while the task of construction thinking is to focus on engineering design. Accordingly, theory is the positive connection between presupposition and conclusion, while engineering is the compound of various substances and their properties. To adopt theoretical thinking while engaging in engineering design would ruin the design; to adopt engineering thinking while building theories would render the theories invalid. Because there is a clear-cut division between the two modes of thinking, which one is appropriate depends on the purpose of the research—to seek objective truth or draw a real-life blueprint (Xu 2001).

Xu's academic opinions may provide insight into the questions concerning the establishment of mega infrastructure construction management theories. Therefore, in the first two sections of this chapter, we present some of Xu's academic thoughts.

3.1 Theoretical Thinking and Construction Thinking in Construction Management

3.1.1 Two Modes of Thinking

It is through the sensory organs, such as the ears, eyes and hands, as well as the brain, which uses language to think, that people come to understand and transform the world.

In practices of engineering creation and construction management, how do people conduct basic thinking activities?

Initially, to satisfy their own needs, humans directly utilized properties of entities in nature, such as natural caves, which could accommodate people, and naturally fallen trees across rivers that could be used as bridges. Humans then created houses and bridges through thinking because they bear the properties of those caves and trees that meet the needs of humans. When the entities in nature no longer have certain existing properties that humans need, people strive to create these properties. "As properties will not exist if separated from entities, the creation of a new property can only be achieved by the creation of a new entity" (Xu 2001). Known as engineering creation, it is necessary to clarify the properties of humans, objects, and environments, as well as the relationships between their real properties and ideal properties, and to well organize and control the creation process based on these relationships, namely, construction management. People involved in construction management must observe numerous phenomena, address a multitude of issues, and obtain relevant thoughts and ideas through feelings and experience to form the knowledge of things through the brain's abstract thinking to obtain a deeper more universal understanding that can provide practical guidance for engineering creation. Thus, principles of construction management that have practical and universal significance to engineering activities are gradually formed beyond some individual-specific engineering entities. These principles can correctly reveal the links and rules between the properties of construction management elements to which general engineering adheres.

In construction management practices, the mode of thinking that seeks to understand the general principles of construction management with the basic purpose of clarifying the characteristics of the object is called theoretical thinking, the product of which is to form the logical system concerning the properties of construction management elements and the links among them.

Theoretical thinking is significant in construction management practice, as it regards the generality of engineering as the object, which is beyond the uniqueness of individual-specific projects. With its main forms of abstract summarization and logical inference, theoretical thinking reduces, as much as possible, the cognitive bias caused by people's preference of values, thus enhancing its objectivity, universality, and scientificity. Therefore, the essential rules of construction management can be revealed as deeply as possible.

However, theoretical thinking also has some limitations. The reasons for those limitations are as follows:

1. Theoretical thinking mainly provides the principles obtained through logical thinking, while, in practical construction management activities, there exist principles obtained through illogical thinking as well as principles from other fields. Therefore, a full knowledge of construction management cannot be realized by solely depending on theoretical thinking.
2. Theoretical thinking obtains mainly general principles of construction management, while, with respect to a specific project, in addition to the general principles, the unique principles of the construction itself should be followed as well.
3. As a cognitive activity of humans, theoretical thinking also has limitations, which lead to potential bias and an incompleteness of the principles obtained as well as to relativity of their scientificity.

Hence, though principles obtained by theoretical thinking provide guidance for practice, do not take it for granted that all practical problems in construction management can be resolved based on theoretical thinking.

In addition, any specific engineering creation that is individual, real, and unique will eventually form a complete and sole engineering entity. Thus, with respect to a certain project, it requires not only the guidance of general principles offered by theoretical thinking but also the awareness of the project's uniqueness and realness obtained by people's perceptions, intuitions, and various modes of illogical thinking. Then, accordingly, the intentions, plans, and approaches that can transform general principles into unique engineering entities are formed. In other words, there should be plans for turning the blueprint of virtual engineering into complete entitative engineering that include specific designs, processes, approaches, and skills.

Only by implementing the plans step by step at the various operational levels will engineering creation achieve practical significance. *With respect to construction management, this mode of thinking, referred to as construction thinking, involves the main task of planning and the purpose of transforming virtual engineering into entitative engineering***.** Thus, construction thinking is another important mode of thinking that differs from theoretical thinking in construction management.

Construction thinking is not for clarifying principles but for determining how to establish construction entities. "Construction thinking takes planning as its value goal, while planning itself should regard the subject's value intention as the starting point" (Xu 2001). Construction thinking can plan not only for a specific construction entity but also for several construction entities. However, as it requires that people directly confront construction management practices, it will certainly be permeated by their value orientations.

Therefore, the following points must be considered:

1. With respect to a specific construction entity, construction management must simultaneously involve theoretical thinking, construction thinking, and other modes of thinking.
2. In construction management practices, theoretical thinking puts forward the targets, intentions, and overall cognition of construction, while construction thinking focuses on the corresponding plans, approaches, and processes. More specifically, the former attempts to succinctly clarify the principles, whereas the latter is concerned with transforming the virtual parts of construction into entities based on these principles; the former proposes standards, whereas the latter guarantees operations, and the former serves the latter, whereas the latter serves construction realization. In the phase of construction entity establishment, construction thinking is the leading mode of thinking. However, as a whole, cognition and planning are unified, as are theoretical thinking and construction thinking (Xu 2001).

It is of great significance in construction management to distinguish theoretical thinking and construction thinking. Specifically, theoretical thinking, in a general sense, is the cognition of general principles. It requires abandoning the details of individual-specific construction management activities, as well as their uniqueness and differences, identifying the commonalities and essence behind these activities and abstracting them to obtain the fundamental rules that bear general significance. These rules, due to their foundation on individual-specific construction entities, should be followed by individual construction entities as well. Actually, it is a matter of realizing the essence of what constitutes construction management and why it operates as it does based on the number of individual construction management activities, which, in turn, reflects the guiding role of theoretical thinking of construction management practices. Thus, *theoretical thinking is primarily the mode of thinking that clarifies the "what" and the "why," forms construction management theories, and establishes theory systems of construction management.*

Nevertheless, construction thinking, as an entirely different mode of thinking, addresses specific construction creation activities, including construction management. The moment construction is specified, people's general intentions and needs must be realized through the completeness and realness of the creation activity, and the uniqueness of specific projects must be fully recognized and respected as well. Only in this way can the specific plans and approaches of construction management be achieved with the combined action of a series of perceptions, intuitions, logics, and illogics. In other words, the principles of construction management must be systematically combined with the practical operational details to configure the complete operational approaches, skills, and processes of construction management. Therefore, the intent of construction thinking is to design processes and operational procedures of construction creation and management and to define and plan correct operational approaches and standard management steps. It is, in this sense, a mode of thinking that clarifies "what to do" and "how to do" in specific operations of construction management for the purpose of implementation and practice.

However, the two modes of thinking should be considered in a correlative, rather than a completely separate, way. In fact, as theoretical thinking is based on the knowledge of general rules and general characters of construction management, such knowledge is gained through the abstraction, summary, and sublimation of numerous specific construction management phenomena. That is, theoretical thinking is obtained from the construction thinking of individual projects, whereas construction thinking, though aimed at specific projects, must be guided and led by general rules that extend beyond certain management activities, thus often adopting non-individual commonality tools and approaches to solve individual problems. This means that construction thinking of individual projects is led by general principles of theoretical thinking, which can reflect practical significance and functions of principles only by permeating the construction thinking of specific projects. Thus, in construction management, despite the important distinctions between theoretical thinking and construction thinking, the two are closely related and integrated in practice.

In conclusion, theoretical thinking and construction thinking in mega infrastructure construction management practices are two of the most significant and fundamental modes of thinking. "The value function of theoretical thinking lies in figuring out necessary connections between properties of different categories, while that of construction thinking consists in combining properties of different relation systems into an construction integrity. The former strives for binding objective principles while the latter for operable subjective designs; the former serves the latter, while the latter serves construction implementation, namely practice" (Xu 2001). Whereas the product of theoretical thinking is the formation of theories, that of construction thinking is the formation of construction entities. A solid comprehension of the connotations and differences of these two types of thinking may provide significant guidance for our understanding and establishment of mega infrastructure construction management theories.

3.1.2 Experience, Knowledge, and Theories of Construction Management

Because this chapter studies the core issue of how to understand and establish mega infrastructure construction management theories, the following section dissects the concept of construction management theory.

In construction management practices, people obtain their cognition and perception of these practices through thinking. As time passes, construction management naturally gains increased understanding of and more experiences in management activities, which, overtime, become increasingly more enhanced. Hence, later, when confronted with similar situations, they will, consciously or unconsciously, draw upon that knowledge and those past experiences for construction management practice. Such understandings and experiences will be further strengthened and improved as management experiences increasingly more successes in practice. Therefore, the understandings and experiences of management activities that people obtain through practice and observations are their experiences in construction management. In this respect, experience can be a certain type of knowledge, a skill or a technique.

In construction management practices, regardless of the time or the place, people tend to repeatedly produce similar experiences with respect to construction management, making it easier to acknowledge and solidify the experience. Accordingly, the experiences become more reliable and valuable, and thus, they provide better guidance for construction management practice.

Experience produced during construction management practice, especially a solidified experience, will become people's knowledge of construction management, as experience is the product of people's systematic understanding of the general rules of construction management activities. Knowledge, which is an inclusive concept, includes facts, information, descriptions, skills, techniques, etc. Any knowledge of construction management must be accurate and practice tested, and it must also be trusted and accepted by the people. Certainly, it is likely that some individual knowledge is independent and scattered and that there exists some correlation among the different knowledge, but generally speaking, knowledge is continuously improving during its process of formation.

If the individual knowledge, which is relatively independent and scattered, is integrated according to certain rules, then it will form and be a part of the body of knowledge and have certain correlations with the various knowledge therein. The project management concept with which we are familiar is the typical body of knowledge concerned with construction management activities. On the one hand, it consists often relatively independent domains of construction management knowledge, namely, integration, scope, time, cost, quality, human resources, communication, risk, procurement, and stakeholder. On the other hand, it reflects the correlation among these domains of knowledge.

Under the guidance of certain principles of thinking and after confirming the essential properties of construction management activities and forming the cognitive *scope, knowledge of construction management can be further systematized and logicalized into theories of construction management*. Theories reveal the general rules of construction management activities more deeply, and thus, they are the updated version of the body of knowledge on construction management. More succinctly, experience is the basic form of knowledge, and theories are the advanced form of knowledge. A theory, with knowledge as its fundamental element, is a systematic and logical body of knowledge. Therefore, theories have natural systematicity; that is, theories of a certain domain, in the overall sense, constitute theory system. For instance, *mega infrastructure construction management theories should be regarded as the mega infrastructure construction management theory system*.

Thus, in what ways are theories more advanced than knowledge?

1. A theory is a systemic body of knowledge.

On the whole, information and facts within the body of knowledge are mostly independent and weakly relevant to each other. It should be particularly noted that knowledge aimed at different problems often assumes different forms in different practices, so such knowledge, with different backgrounds, premises, conditions, and boundaries, is relatively independent. For example, knowledge of construction quality management and knowledge of construction cost management, because of their distinctions in technical backgrounds and in the nature of the problem, show tremendous differences and prominent independence.

However, the bodies of knowledge within the various construction management theories are relatively more relevant to each other. First, during its formation, the awareness of the knowledge regarding the properties of construction management activities must be consistent. That is, the body of knowledge should reflect consistency in the principles of theoretical thinking and embody a universality of theory based on that consistency to more completely address construction management activities and the various problems therein. This can only be realized, however, with a well-designed system. Furthermore, there must be fairly strong cohesiveness and extensiveness between the knowledge within the theories; that is, the knowledge must be closely correlated so that new theoretical elements can be formed to solve new problems as they arise. However, this can only occur given a highly systematized body of knowledge. Finally, a theory system of higher quality would provide guidance and regulation for the corresponding methodology and thus intensify the overall functionality of the theories. In this sense, theories must consist of systematic knowledge, rather than a collection of scattered and isolated knowledge points.

2. A theory is a logical body of knowledge.

To reveal the essential properties and inner rules of construction management activities, construction management theories must be capable of abstracting and thinking based on the words that reflect these specific properties. The words not only have their own connotations and contexts but also have connections with each other and with the objects, which require that theories adopt people's language habits and language logic. Although the many countries and nations worldwide use different languages, with different language logic and habits, the mega infrastructure construction management theories are the common cognition of nations using different languages regarding the essential properties of man's mega infrastructure construction management practice. Thus, theories should possess a more advanced scientific language system that surpasses the general logical relationship of natural language and exhibit a corresponding logical system. Furthermore, to explicate the phenomenon of construction management activities, reveal the objective rules therein, and provide guidance for practice, theories must produce new understandings and knowledge through inference, judgment, and other modes of logical thinking. This requires that theories have a specific logic and rules so they can guarantee the fundamental qualities of standardization, definitiveness, organization, consistency, etc. More specifically, construction management theories must have their own core concepts on which they are based, deduce developable fundamental principles and extract universal scientific problems. All of the aforementioned aspects must be conducted under the logical framework of the scientific language system. Therefore, a theory must be a logical system with knowledge as its basic element.

Accordingly, experience, knowledge, and theories of construction management of the same origin are consistent with each other. However, during the formation process of a theory, its scientific connotation and quality will exhibit the progressiveness and maturity of its constant systematicity and logicalness.

The basic cognition and quality judgment of the construction management theories are, in principle, consistent with those of mega infrastructure construction management theories.

3.2 PMBOK and Its Theoretic Position

After clarifying that knowledge and theory have the same origin and distinguishing their essential differences, we can analyze a basic question, that is, whether the Project Management Body of Knowledge (PMBOK), which plays an important role in construction management practices, can be regarded as the mega infrastructure construction management theory system. This question is significant because it helps to differentiate two future work directions. If it can, we need only to develop and improve the theory system within the framework of project management; if it cannot, then we must develop a new theory system from the beginning. Obviously, these two directions are of completely different natures.

It is well known that the PMBOK has been preeminent in the profession of project management for decades. Blueprints and operation processes for construction management have been designed, gradually given form and finally been standardized on the basis of organizing and summarizing practical experiences and knowledge in the field of construction management. Furthermore, they have been playing an important role at countless construction management sites. Recent years have witnessed annual adaptations and expansions to *A Guide to the Project Management Body of Knowledge* (the *PMBOK Guide*) and also witnessed the book's increasing power as a guide. While all in the profession think highly of the *PMBOK Guide*, some express a further hope that a typical form of a mega infrastructure construction management theory system could be developed by either directly borrowing the system detailed in the *PMBOK Guide* or by modifying it to better fit mega infrastructure construction management. This is an important notion for building a theory system in the research field of mega infrastructure construction management. Based on our understanding of construction management theory as a concept, we must compare the thoughts reflected in the mega infrastructure construction management theory system with those reflected in the PMBOK, judge the theoretic position of the latter, and decide whether the situation is appropriate for the body of knowledge to work as a theory system. The conclusions will determine our view of and attitude toward the development of a mega infrastructure construction management theory system.

3.2.1 Overview of the PMBOK

The recent century has seen an increase in both the number and size of construction projects, which has led to increasingly sophisticated construction management organizations, a constant emergence of new management techniques and methods and, thus, a growing trend toward more diversified management approaches. This development in the construction management field has encouraged thorough consideration of how to standardize and optimize construction management activities so that standardized guidelines and processes can be developed to cope effectively with the wide range of problems that arise at construction management sites and to meet the training and development needs of construction managers.

One important historical event that achieved great success is traced back to the 1950s or 1960s when America employed the ideas of system analysis and system construction to decompose the tasks in military construction management and then reorganize the components into processes. This event also served as a great motivator for the standardization and optimization of general construction management. Accordingly, the PMBOK that we see today is developed against this background.

It has been approximately 50 years since the PMBOK came into being, and since its birth, corrections, revisions, improvements, and expansions have been ongoing (Ghosh et al. 2012; Poddar et al. 2011; Sliger 2008; Wideman 2002), indicating that as the scope of construction management broadens, the importance attached to the design, distribution, and integration of construction management activities and to the techniques and processes involved becomes increasingly greater.

It is further noted that although the PMBOK drew on the ideas behind system analysis and system construction and although a series of specified areas of knowledge and management processes have taken form, as the project management system evolves, the focus has been on how to effectively solve real problems encountered at construction management sites. During this process, the direct applications of the fundamental ideas of system analysis, ideas based on reductionism, such as decomposition and analysis, have been witnessed, but neither of these has the essence of systems science, especially that of complex systems science, and neither has been fully utilized. Moreover, neither paths nor principles have been established in accordance with theories, and thus, no systematized or logical knowledge concerning construction management has been developed. Rather, under the stimulation of people attending the PMI certificate training program and within the boundary of various specialized management functions, the PMBOK has gradually been solidified by combining the systems reduction theory and the ontology of construction sites as tools, techniques, and skills to guide real project site operations.

In 1976, the PMI advance the notion to establish standards for project management, and after a 10-year study, the PMI issued the 1st edition of the *PMBOK* in 1987 (Duncan 1998); in 1996, its name was changed to the *PMBOK Guide*. The *Guide* divides project management into nine areas of knowledge, which are further divided into 37 management processes, each with a description of bases, tools, techniques, and results presented in that order. This layout facilitates the assembly of knowledge in those areas and makes the structure of the entire knowledge system more flexible, thus making the reorganization of management processes much easier (Duncan 1998; Project Management Institute 1997, 2004, 2009, 2013). This PMBOK layout, with specified cause-effect relations and similar to a structure constructed with toy blocks that can be easily dismantled and then reorganized, becomes the basic paradigm of the PMBOK that exists today.

To date, there have been five editions, the second one being published in 2000. Each of these editions, marked with distinctive features specific to the era when they were issued, represents not only the continual focus on and response to the then latest, most common, and most important questions and tasks in the field of construction management but also the evidence of the management experts' ambitions and commitment to being caution, rigor, and preciseness. For example, the 2nd edition not only improves the connections among the areas of knowledge and further divides the processes but also emphasizes the management of projects as a whole; the 3rd edition expands the scope of management and displays an awareness of management process control; the 4th edition proved a more in-depth exploration of such concepts as people-oriented management and standardized management and attaches greater importance to the management of information and data in construction projects; and the 5th edition not only includes a section dedicated to just stakeholder management but also discusses the five management processes. Furthermore, the 5th edition also changes the name of construction project management and established corresponding rules for the input/output of a process to address the possible ambiguities that may arise in increasingly complex construction management tasks. These changes reflect the need for construction project management to remain concise and specific.

The 50 years since the 1st edition of the *PMBOK* was issued is a period during which experiences in and knowledge of construction management practices have been summarized, organized, and integrated while practices continue to evolve, a period during which construction management processes centering on different areas of knowledge have been organized under the orientation of "achieving an objective on time, within planned costs and in accordance with its scope," and a period during which the operation guides and behavior standards for construction management, which consist of ten sections in the body of knowledge, have been developed and given form.

Generally speaking, the series of the *PMBOK Guide* places special emphasis on the introduction of knowledge, methods, and skills needed in construction management operations. The areas of knowledge are comparatively independent, and the logical relations among elements in the same knowledge area are clearly described by adopting the input-output model. Each section in the body of knowledge has three basic components, namely, input, tools (techniques), and output, which are integrated as if they were connected to form a chain. During this integration process, important knowledge elements are combined within those sections such that the application of knowledge can be displayed in specific construction management scenarios.

In addition, from the nearly 50-year evolution of the *PMBOK Guide*, it is evidenced that as construction management activities became increasingly varied, management problems became increasingly more complex, and management processes became increasingly longer, the *Guide* tracked this growth and spared no effort to maintain pace with the practical needs of construction management (Duncan 1998; Indelicato 2009; Project Management Institute 1997, 2001, 2004, 2009, 2013).

For 50 years, the *PMBOK Guide* series has played a huge role in the organization and management of various constructions and will continue to be of great practical value and significance even though the series will face challenges from complex mega infrastructure construction management.

Today, when the development of the mega infrastructure construction management theory system is discussed, an important, indispensable, and antecedent issue is to study and evaluate, in great depth, the ideas behind the PMBOK and its theoretical value.

3.2.2 Analysis of the PMBOK's Theoretical Model

An analysis of the content, structure, and function of the *PMBOK Guide*, especially of its role in construction management practices over the years, provides insight into some of its important characteristics:

1. The thinking behind project management is to make full use of limited resources to accomplish planned goals based on a set of management techniques and standardized processes developed as a result of the effective planning, coordination, and control exerted by certain organizations under specific operating mechanisms within a clearly defined time limit. The *PMBOK Guide* defines the clear boundaries for construction management activities, decomposes the overall task into separate, smaller tasks, and matches those decomposed tasks with their corresponding departments or units within the organization. That is, inspired by

reductionism, people decompose the management functions based on the belief that 2 = 1 + 1. This reflects the understanding that the management of the whole equals the management of its component parts. More importantly, though the *PMBOK Guide* places greater emphasis on the relevance of different knowledge areas, its overall structure suggests that the design and description of management tasks and their functions are confined within those individual areas and that there is no breaking of bounds or blending beyond boundaries. The expansion of the management field over the years is mirrored only in the increased number of areas or in the small changes made to management processes. Thus, no changes have been made to the overall independent structure of the management field.

The understanding of the PMBOK with respect to reductionism is reflected in its view of general systems, a view that is applied primarily to comparatively easy construction management practices whose overall tasks can be decomposed or partially decomposed. However, in recent years, a large number of mega infrastructure construction management practices have put the PMBOK at its wit's end. For problems that cannot be solved effectively by the PMBOK, management must rely on human experience and wisdom as their main resources, as no new theory has been developed and adopted to guide mega infrastructure construction management practices. This is one of the reasons the PMBOK is challenged by the needs of mega infrastructure construction management to the point that the tension becomes palpable.

2. The specific content of the areas of knowledge in the PMBOK includes a phase-by-phase design of how to conduct the basic tasks at a construction management site, a clear choice of bases, tools for each stage, and the relevant accomplishments/results that must be reported once the tasks are completed. These are blueprints to guide specific operations in construction management and are "what to do" and "how to do" designed for engineers to follow when implementing management activities, as they explain how to execute the plan at construction sites. Accordingly, this is a specific reflection of construction thinking designed for construction management practices.

Based on this analysis, it is evident that though the PMBOK has been enriched and improved in terms of its content, it has become increasingly inclusive for the last several decades. This has led to the favorable result that the PMBOK keeps pace with the growing needs of construction management needs; however, its overall thinking model and functions, among other things, remain unchanged, as reflected in the following two points, respectively:

1. Based on the thinking that combines reductionism with respect to construction management with the ontology of the construction site, the PMBOK decomposes tasks into their component parts that can be combined later, designs and plans blueprints for those component tasks within comparatively separate knowledge areas whose boundaries are clear and whose functions are specified, and describes the standardized operation processes and methods, which are believed to be ideal within those areas. At this point, the processes and methods need only to be implemented.

2. Though the complete realization of a construction entity requires a combination of theoretical thinking and construction thinking, the PMBOK does not explain, by building a logical structure or revealing its design features or attributes, what construction management is or why it is. Rather, the PMBOK is a combination of knowledge and techniques that explain "what to do" and "how to do." In this way, it provides guidance in specific construction management practices.

It is important to note that the PMBOK is the result of certain thinking models, among which construction thinking is the dominant model. This is an important factor given that construction thinking unavoidably reflects the values, intentions, and preferences of the subject, and thus, the PMBOK could negatively influence or damage the objectivity of the subject, which, in this case, is construction management. This is also one of the reasons that a system based on construction thinking cannot evolve into a theory system.

3.2.3 The Theoretic Position of the PMBOK

As the *PMBOK Guide* series is the result of the continual growth of construction thinking, we analyze the theoretic position and theoretical value of the series, as they are more closely associated with the goal of building a mega infrastructure construction management theory system.

As previously stated, the word theory, as mentioned herein, refers to the complete theory system in a field, i.e., a systematic and logical body of knowledge in the field (see Sect. 3.1). It is neither a specific theoretic question nor a collection of theoretic questions that are comparatively independent of one another or loosely connected to one another.

In recent years, as the *PMBOK Guide* developed, there has been a gradual increase in discussions about the theoretic questions. This is because the *PMBOK Guide* spares pages, though to different degrees, to explain "what" and "why" questions about construction management phenomena while standardizing "what to do" and "how to do" processes. That said, these explanations serve primarily as evidences or bases for the "what to do" and "how to do" questions. That is, they do not aim to reveal the universal rationale for construction management at the design feature level under the same principles of thinking. This suggests that those explanations are wanting in both depth and width with respect to a theory system. Therefore, we cannot conclude that the *PMBOK Guide* has evolved into or represents a theory system. In addition, an important difference between knowledge and theory is that the latter is systematic and logical. However, in reality, people believe that different pieces of knowledge that are related to one another or that originate from the same background are systematic and logical. In fact, a systematic and logical knowledge must have one fundamental attribute, namely, a logical system created by people at a theoretic level guided by the same principles of thinking and based on a common scientific language.

However, there are deviations from this opinion of the fundamental difference between knowledge and theory system, which leads to ambiguity over our understanding of project management knowledge in terms of its theoretic scale and over the judgment of its theoretic position. One of the typical examples is the frequently heard statement that project management is a broken construction management theory. There is something incorrect about this statement, however:

1. Construction management theory as mentioned herein should be a theory system, not just one or several independent theoretic ideas. A theory system should have specified and strict scientific ideas and fundamental rules and should not be ambiguous or mechanically employed.
2. We cannot determine what construction management theory is or is not before we specify the scientific ideas and fundamental rules within the theory system.
3. There is no situation where a theory system can be broken, as being broken violates the basic requirement of a theory system to be systematic and logical.
4. The scientific statement of a theory system must abide by the same scientific principles of thinking and must use standard scientific language. Ambiguous natural language cannot be used to describe the theory system, or the scientific ideas will easily become blurred, leading to an ambiguous statement.

Accordingly, it is safe to say that only by the analysis and confirmation of the profound ideas behind the construction management theory system can we accurately define the theoretic qualities of the theory system and design a path for forming the theory system.

First, as previously analyzed, with respect to relatively simple construction projects, the practices employed by the projects would naturally be relatively simple and without the distinct feature of system complexity. For example, the goals and tasks of construction management can be decomposed within the overall framework into several areas that have weak relations, which is mostly independent of one another. For this type of project, the thinking that combines reductionism and the ontology of the construction site not only indicates "what to do" and "how to do" but also answers questions about the management object, such as "what it is" and "why it is." This is because, for relatively simple questions, the solutions and the rationale behind the solutions are closely related, and there are no major differences between question descriptions and their connotations.

Second, since relatively simple construction projects have comparatively independent management areas and because there is a clear logical relation among the knowledge within each of the areas, the knowledge is systematic and logical when the knowledge from each of the areas is added together or when a certain sequence or process forms after the knowledge is listed out prior to it being sorted out. Therefore, at the practice level, the *PMBOK Guide* integrates different parts of construction management knowledge by dividing the knowledge into sections or areas, a process in which the knowledge is systematic and logical and at a relatively low level. That is, for relatively simple construction activities, the *PMBOK Guide* can be regarded, to some extent, as a collection of systematic and logical knowledge. Thus, for relatively simple construction activities, the *PMBOK Guide* represents a theoretic knowledge about construction management at a comparatively low level.

Furthermore, since this type of construction management has neither the obvious feature of systems complexity nor as many complex problems that threaten to deactivate the belief that the combination of the parts equals the original whole, as represented in the thinking of reductionism, there is an acceptable small error/deviation between the *PMBOK Guide*, which is created under the guidance of the systems thinking and technical route centering on reductionism, and the construction management task itself. In other words, the thinking and technical route is practical, and thus, people can use their experiences and wisdom to address relatively complex management problems in actual practice when the *PMBOK Guide* fails. Though there are times when PMBOK does not function well, it can still manage the challenges imposed by mega infrastructure construction management. However, with the increasing number of complex construction management problems, it is increasingly difficult for the *PMBOK Guide* to address all of them, a situation that presents a tension point for the PMBOK.

From the above analysis, we derive the following important conclusion:

As to relatively simple construction management activities, there is a channel connecting what the PMBOK says and the plans regarding construction management and logical and systematic knowledge such that the distance from theoretical thinking and construction thinking is rather short. Therefore, the *PMBOK Guide*, as result of the combination of reductionism and the ontology of the construction site, frequently not only describes the ideal blueprint for construction management, telling people "what to do" and "how to do," but also reveals the attributes of construction management, letting people know "what it is" and "why it is." However, only when the construction environment and conditions are relatively simple can the *PMBOK Guide* display its theoretic quality by bringing into play its techniques.

It should be noted that the theoretic quality the *PMBOK Guide* displays refers to the words that explain and illustrate the rationale behind the techniques used at a specific construction site. It should be regarded more as an explanation of knowledge that is still lacking in completeness and maturity with respect to its ideas and its function as a paradigm.

For that reason, the *PMBOK Guide* generally cannot be regarded as a construction management theory system, or, to give it a less important title, as a defective construction management theory system under improvement. As the *PMBOK Guide* is the result of construction thinking, not theoretical thinking, there is a great difference between how it is formed and how its results are described and between the general patterns and paradigms behind theory systems.

In fact, for many years, engineers and experts have been dedicated to answering questions such as how to construct and how to directly and effectively solve the large number of real problems arising from construction sites. Although people are thinking more about theoretic questions concerning construction management, theoretic questions and theory systems are two completely different concepts, and by contrast, the former is an individual theory, whereas the latter is systematic. The study of one theoretic question may result in only one or two points of knowledge, whereas building a theory system is a fundamental and long-term task that spans several study fields, and thus, the process requires a necessary accordance with the standards to form a theory and with the systematic principles and patterns of a theory system.

For several decades, due to the important role the *PMBOK Guide* has played in practice and due to the powerful effect reductionism thinking has exerted on construction management, there has been tremendous progress in construction management practices and on the long-term absence of a construction management theory system. Not surprisingly, the tension between the two sides has been increasingly felt.

Referring to the question mentioned at the beginning of this section, if the *PMBOK Guide* cannot be regarded as a standard construction management theory system built upon theoretical thinking, then on the whole, a standard mega infrastructure construction management theory system does not exist either. While it may be shocking to realize that there is a huge, serious gap between mega infrastructure construction management theory and practice, this is the status quo in the research field of mega infrastructure construction management, a reality that must be accepted and upon which action must be taken immediately.

After analyzing the PMBOK and its theoretic position, the author contends that it is necessary to stress the following perspective to remind readers of the great significance and effect of the PMBOK.

Specifically, after considerable analysis, the author concludes that the "*PMBOK Guide* cannot be regarded as a standard construction management theory system built upon theoretic thinking." This conclusion is based on the two thinking models employed in construction activities and their main functions, on the different stages an object is understood to experience and on how that understanding evolves. This conclusion is actually an evaluation of one of the PMBOK's functional attributes, namely, theoretical value, where the evaluation is based on the value standard behind the logical system of thinking and understanding, a system created by people. It is important to note that this is only an evaluation of the PMBOK's function according to an artificial logical system of thinking and understanding, though the PMBOK actually has functions that are multilayered and multidimensional. In addition to the functional attribute of its theoretical value, the PMBOK has other important functional attributes, such as management techniques and methods, which, because of their tremendous guidance significance, have played important roles in construction management practices. This book does not doubt or deny any of these contributions; rather, it offers affirmations. All conclusions offered herein are made under certain conditions and with specific premises; thus, the conditions or premises should not be confused, or conflicts among different conclusions will be created.

The author contends that the conclusion regarding the PMBOK's theoretic position, which is based on an in-depth analysis, specifies the PMBOK's duality, i.e., the presence of its practical effects and the absence of its theoretical value. This is more subtle and profound than the mere evaluation of the PMBOK's significance and effects, without making distinctions between the practical dimension and the theoretic dimension. It is beneficial to have a scientific understanding regarding the application of the PMBOK's significance to face the challenges imposed by increasingly complex construction practices and to innovate and develop construction management theory.

3.3 Mega Infrastructure Construction Management Theories Under Development

Under the current background and status quo of the field in question, construction management experts around the world have realized the significance and necessity of establishing a mega infrastructure construction management theory system and, aiming for breakthroughs in related research, have been striving to capture major opportunities for the development of such a theory system.

In this respect, in addition to related exploratory studies conducted from various perspectives by construction management experts over the past few years, a new research mode has recently come into being by which multinational experts cooperate to conduct research. For example, in August of 2014, Professor Bent Flyvbjerg of Oxford University in England published an article in IJPM that appealed to construction management experts worldwide to search for a classic theory system of mega infrastructure construction management. A classic theory system, as used herein, can be interpreted as a theory system that is established following the standardized conventional theory-forming path.

The main point of professor Bent Flyvbjerg's article is that between 2013 and 2030, the global average annual expense for infrastructure is estimated to reach $3.4 trillion, the majority of which will be spent on the construction of large-scale projects. Economists, referring only to the field of infrastructure, call it "the biggest investment growth period in history."

In view of the present situation, academic knowledge of mega infrastructure construction management has never seemed as important as it is today. However, one wonders whether the corresponding academic theories have kept pace with the advanced development of practice and whether there are any classic theories that can guide the decision-making process and realize optimal management in mega projects.

A theory can be considered classic if it is widely acknowledged by experts in the field. According to this definition, are there any classic theories in construction management research? If so, what are they, how did they become classic, and what are their effects? If not, why not? Will the classic theory system impact mega infrastructure construction management? Why or why not? Is it possible that mega infrastructure construction management may thrive without the guidance of any classic theory system? Assuming that the classic theory system is important, how should it be developed? What can we learn from other academic fields for the development of such a system? Can the latest version of PMBOK published by PMI in America in

2013 be considered a classic theory system in mega infrastructure construction management? Is it connected with mega infrastructure construction management? How is it related to academic research? Has it impeded the formation of a mega infrastructure construction management theory system in academic research?

Professor Flyvbjerg, in his not-so-lengthy article, proposed a series of closely related, ordered academic questions that are completely consistent with the analysis presented in the beginning of Chap. 3.

Coincidentally, as early as 2003, EPSRC in England funded a research project titled “Rethinking Project Management” whose aim was to redefine, expand, and consider the concepts and basic approaches of project management and to develop the research agenda for the future. This project referred to previous project management theories as Traditional Project Management-1st Order: PM-1 and called those that took into consideration project complexity, globalization, and technological innovation management Project Management-2nd Order: PM-2 (Cavanagh 2012; Ghosh et al. 2012; Hydari 2013; Saynisch 2010a, 2010b). From the perspective of PM-2, project management has begun to develop from the traditional life cycle mode to a complex project management theory that involves the establishment of new theories and models that discern various levels in a project and in project management as well as manage complexity. A project should be considered as a social process in which the management subject should focus more on the behaviors of the people involved, the social interactions, the stakeholder relationships, and the intertwined relationship between policy and power during the process of project implementation (Svejvig and Andersen 2015; Winter 2006; Winter et al. 2006a, b).

It is evident that, currently, the mainstream academia in construction management has, without prior consultation, reached the following consensuses on the issue of mega infrastructure construction management theories:

- There is no classic mega infrastructure construction management theory system thus far.
- The critical point for the formation of a mega infrastructure construction management theory system has arrived.
- It remains uncertain whether PMBOK can be developed into a mega infrastructure construction management theory system.
- Assuming that mega infrastructure construction management theories are of great significance, their establishment and development must be determined.

As all of these issues are important, any research on mega infrastructure construction management theory systems would fall short of logicality if it failed to answer to address one of them.

That said, conducting research on mega infrastructure construction management theories by gathering research resources on a large scale is both unprecedented in history and rare in other subject areas. Nonetheless, it profoundly reflects the increasingly important guiding role of objective rules and of the dialectical relationship between man’s theoretical thinking and construction thinking in the research field of mega infrastructure construction management. It also shows that when mega infrastructure construction management practice reaches a certain stage of development, especially when it approaches or has reached a critical state, the emergence of a theoretical system in this field becomes a natural outcome. Notwithstanding the various occasionalities during the formation of the theory system and certain milestone events, the general trend is inevitable, objective, and historic.

Accordingly, this book holds that when dealing with such an important academic issue as a mega infrastructure construction management theory system, we should approach it from the cognitive level of the human thinking mode. If we compare such a theory system to a huge tree in the field of construction management, we must first determine in what type of soil this tree grows best, what genes and mechanisms will enable its growth, and what type of natural environment and conditions the tree requires. In other words, we must think about the questions at a higher academic level and in a broader academic field rather than confining ourselves to the field of construction management. For example, we should discuss the following questions first:

- What are the basic conditions and environment needed for the formation of a theory system in the field?
- What is the scientific implication of a theory system? What are its symbolic theoretical elements and structures? How can we ensure the normalization of its formation process?

As a final outcome of thinking, a mega infrastructure construction management theory system should be a systematic whole, but in its initial stage, engineers and experts should be open-minded and should explore the design of the structure, the function and logic of the theory system from different angles, and the levels and perspectives of the system. They should also accumulate experiences and achievements during their broad exploration; it should be noted that, during the entire process, they must maintain scientificity of thinking and guarantee normalization of the formation path of the system.

As analyzed previously, as the PMBOK cannot act as a normalized and mature construction management theory system, let alone be considered a mega infrastructure construction management theory system, we must first decide the starting point for establishing such a system, and then, beginning from this starting point, develop the formation path and identify the theoretical components and logical framework of the theory system.

Obviously, these issues involve, on an academic level, far more than traditional construction management. Therefore, we must continue to explore the academic broadness and normalization of studying such a significant issue, as only in this way are we able to view the panorama of mega infrastructure construction management theories and approach their formation path using the correct mode of thinking.

This requires some preliminary preparatory work.

3.3.1 The Basic Implications of Mega Infrastructure Construction Management Theories

According to the general definitions of theories, one can easily understand that *a mega infrastructure construction management theory system is a systematic and logical body of knowledge about mega infrastructure construction management. It is important to realize that mega infrastructure construction management theories equal a mega infrastructure construction management theory system.*

In Sect. 2.3, we mentioned that the general question of mega infrastructure construction management is composed of sub-questions at three levels, specifically, programming and standardization, systematicity, and complexity. The sub-questions at each level contain corresponding management knowledge. Knowledge regarding mega infrastructure construction management belongs to complexity management knowledge at the highest level, whereas the body of knowledge regarding mega infrastructure construction management requires the aggregation of knowledge of various subjects. Moreover, because the general question of mega infrastructure construction management consists of many complicated new sub-questions, it is necessary to weave together knowledge about various aspects to generate new knowledge and new approaches. For example, with respect to complex mega infrastructure construction decision-making, we must combine knowledge of science, human experience, and knowledge and wisdom with computer data processing ability to develop new analysis techniques and evaluation capabilities.

In Sect. 3.1.2, it was stated that a theory is a systematic and logical body of knowledge and noted that *the basic cognition and quality judgment of construction management theories are consistent with those of mega infrastructure construction management theories in principle*. This issue requires further clarification while taking into consideration the characteristics of mega infrastructure construction management.

First, due to the complexity of mega infrastructure construction management (Gidado 1996; Saynisch 2010b; Zhai et al. 2009), both the integration and synthesis of related knowledge units are required, as it should be in this sense that we interpret the systematization of knowledge in mega infrastructure construction management theories (Flyvbjerg et al. 2003; Saynisch 2005, 2010b).

Furthermore, identifying and understanding the logical relationships among the knowledge elements in mega infrastructure construction management, such as the relations among subordination, inclusion, coordination, connection, and feedback, together with deduction, judgment, and reasoning, will facilitate our understanding of the phenomenon of mega infrastructure construction management and will help us solve related problems. We should also generate and derive new knowledge from systematic knowledge groups and chains. In this way, the logicalization of knowledge transforms the mega infrastructure construction management theory system into a self-generating, self-developing, evolving body of knowledge and living theories.

For example, system complexity is the essential quality of mega infrastructure construction management. To be specific, it is the synthetic complexity of the artificial compound system in mega infrastructure construction formed by the logical organization of the complexities of the management subject, managing problems and managing environment. Therefore, we should evaluate the logic of different aspects of complexity knowledge to form the general knowledge necessary to describe and analyze the synthetic complexity of the artificial compound system, and then, focusing on such knowledge, we should conduct research on serial complex management problems in mega infrastructure construction.

Only in this way, after the systematization and logicalization of the knowledge, are mega infrastructure construction management theories able to guide us, based on our awareness of the essence of mega infrastructure construction management and by means of a normative thinking mode, in our research of the complex problems in this field, especially those problems that reflect the essence of mega infrastructure construction management.

To sum up, mega infrastructure construction management theories are a systematic and logical system created during construction management practices and thinking activities, and knowledge is the basic element of these theories. With the help of this system, it is easy to describe and understand the various phenomena in mega infrastructure construction management practices and to reveal the essential properties and general rules of management activities, as such a system has been endowed with the quality of being able to study the essential qualities of the research object in a systematic and logical manner.

Finally, because the would-be built mega infrastructure construction management theory system has such qualities, when it intends to explain the intrinsic properties of mega infrastructure construction management problems and activities, the system will expound profoundly the essence of mega infrastructure construction management, thus distinguishing it from management in other fields, and it will also demonstrate the foundation of its existence and development, namely, the fundamentality of its theories.

Additionally, when we compare general theoretical elements, individual theoretic questions, theoretical topics, and groups of theoretic questions within the category of mega infrastructure construction management theories, this theory system captures an original place. That is, the logical framework and basic elements of the system are of fundamental and original significance to the development of mega infrastructure construction management theories, and all of the other theories are formed as a result of extensions and expansions under this logical system.

This means that the would-be theory system bears the theoretical and academic qualities of fundamentality and originality, and as such, it belongs to the basic theories of mega infrastructure construction management. In this sense, *such terms as mega infrastructure construction management theories, mega infrastructure construction management theory system, and basic theories of mega infrastructure construction management are consistent and synonymous within the academic ideological framework of this author*.

3.3.2 Explanations of Several Related Issues

Several issues closely related to mega infrastructure construction management theories require discussion and explanation. While some are academic thoughts, some are technical routes, and others are specific working arrangements, all are of great importance and require clarification.

1. Orientation

The book contends that the most urgent task is to clearly propose a significant academic goal, namely, to develop mega infrastructure construction management theories. At present, there is no normative or even partially developed theory system for mega infrastructure construction management theories. It is further suggested that this task be developed from the ground up and conducted according to normative requirements and procedures of development.

2. Norm

Mega infrastructure construction management theories should adhere to the rules and requirements of the formation of general theory systems (explained in Chap. 4). Though with respect to mega infrastructure construction management theories, much can be learned and applied from other academic fields, which should be encouraged; this will not work if the new theory system simply adopts the entire theory system of another field as its standard, projects the theoretical problems of mega infrastructure construction management onto this norm, and then interprets these problems based on the academic thoughts, language, and approaches of this other field. Such a parasitic method is not the normative formation path for mega infrastructure construction management theories nor can mega infrastructure construction management theory be developed merely by widely applying theoretical thoughts and approaches of a certain field or several other fields without unified principles of thinking.

Because neither of these practices profoundly reflect the essential properties of mega infrastructure construction management activities and management problems at the practical and cognitive levels, neither the integrity of the systemization and logicalization of knowledge nor the consistency of the principles of thinking can be guaranteed. If some concepts and words borrowed from new fields of science are used to interpret problems of mega infrastructure construction management, they may have small-scale or isolated significance, but they would be unlikely to support the entire theory system, as they would be lacking in practical philosophical guidance and essential connotation of theories. The above examples further support that the establishment of mega infrastructure construction management theories must adhere to the general rules of theory formation.

3. Relativity

For any theory system, the principles upon which it is founded and the rules it reveals are all relative truths; that is, they are all relatively correct, relatively profound, and relatively comprehensive. Thus, theories can only be relatively true. We cannot rely on a theory system to solve all of the practical problems of mega infrastructure construction management. It is particularly noted that in mega infrastructure construction management practices, in addition to logical thinking, there is also illogical thinking as well as many other thinking modes. Accordingly, in mega infrastructure construction management practices, it is not acceptable to have no theory system, but it is also wrong to adhere to a philosophy of "theory system only."

In addition, mega infrastructure construction management theories should not be considered and understood as unique. Rather, as many management thoughts and management schools do, an open and emanative attitude should be taken toward establishing a mega infrastructure construction management theory system. Only in the developing trend of "letting a hundred flowers bloom, let a hundred schools of thought contend" can mega infrastructure construction management theories come smoothly into being.

4. Chronicity

It is not easy to develop a mega infrastructure construction management theory. The amendments, improvements, expansions, and upgrade require long-term arduous exploration. Mega infrastructure construction management is a broad and profound concept that is closely related to time, space, region, construction type, environment, culture, systems, history, and policies, and it is easily influenced by the subject's perspective when observing problems and thinking about questions. The problem of mega infrastructure construction management itself is also extremely complicated. Taking all of this into consideration, it is essential that we iterate and develop a correct understanding of the management problem. Therefore, the development of mega infrastructure construction management theories is a goal and a task that demands long-term, step-by-step efforts and the work of numerous experts. Given this, it is a job that will likely never be finished.

5. Practicality

Although the study of mega infrastructure construction management theories is primarily conducted at the level of theoretical thinking with respect to mega infrastructure construction management activities, the researchers must be firmly grounded in the practice of mega infrastructure construction management because all products of people's theoretical thinking are the results of reflection and the abstraction of practice.

In this regard, China is gifted with special conditions. To conduct theoretical considerations of mega infrastructure construction management, China has profound backgrounds and origins. China is currently one of the leading countries with respect to the total number of mega infrastructure constructions and the scale of single mega infrastructure constructions. According to the relevant statistical data released by IMF and UNESCO in 2013, the number of mega infrastructure constructions either constructed or under construction in China between 1945 and 2012 is 7932, which is classified as superabundant. In comparison, for the same period, the USA reports 5155 projects, which is classified as many. Countries whose numbers are classified as relatively many include Russia with 3729 projects, Brazil with 2,931projects, India with 2435 projects, Turkey with 2177 projects, and France with 2004 projects (Ansar et al. 2014; Flyvbjerg and Budzier 2013; Flyvbjerg 2011; Hu et al. 2015). China is also the country that, since 1990, has built the most mega infrastructure constructions in the world. Though the statistical data are not totally unified and complete and the numbers of constructions are not exact, the general conclusion is considered credible.

Considering individual construction as an example, China's Three Gorges Project, one of the largest mega hydraulic projects in the world, has simultaneously incorporated functions related to flood control, power generation, navigation, water supply, etc. The total capacity of the Three Gorges Reservoir is 39.3 billion cubic meters, and the total installed capacity and annual power generation of the Three Gorges Hydropower Station, which is the largest in the world, are, respectively, 18.2 million kilowatt-hours and 84.7 billion kilowatt-hours. The amounts of earthwork, concrete, etc. used for the project's main constructions are the largest in the world. The project, with a gross investment of more than 330 billion RMB, is regarded as the largest infrastructure project in China since the construction of the Great Wall (Dai et al. 2006; Fu et al. 2010; Kepa Brian Morgan et al. 2012; Suo et al. 2012; Webber 2012).

As a great power in mega infrastructure construction in the contemporary world, China, on the one hand, has made great achievements in construction and vigorously boosted its social and economic development. On the other hand, China has gained rich experience in mega infrastructure construction management, which is beneficial to the exploration and reflection of mega infrastructure construction management theories based on what we have learned about construction management practice.

Thus, the current status quo of mega infrastructure construction management strongly demands the development of mega infrastructure construction management theories. In the meantime, the constantly enriched practice of mega infrastructure construction management, the continuously growing research team, and the accumulated research products have provided abundant fundamental conditions for the establishment of a mega infrastructure construction management theory system. That said, the development of mega infrastructure construction management theories is in an embryonic stage.

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Chapter 4
The Formation Path of Mega Infrastructure Construction Management Theory

According to the author's understanding, developing a mega infrastructure construction management theory (system) is a complex project that involves the building of a knowledge system and then the promotion of that system. The core task is to adhere to the general rules for developing a theory, consider the essential elements of the theory and their logical relations with one another as the foundation, and then design and transform the theory (system) into a structure. During this process, it is necessary to identify the principles of thinking behind the theory system, the essential theoretical elements, the concepts and fundamentals that can be derived from these elements and concepts by logical judgment, and the basic abstractions that can be further extracted from the fundamentals of mega infrastructure construction. To form basic abstractions means to develop basic scientific questions. Although each of these steps is relatively independent of the others, they are logically related to the others. As a result, a complete structure of a theory (system) can be developed as follows: *principles of thinking (category theory), substantial concepts, fundamental principles, and scientific questions*.

In other words, *to develop a mega infrastructure construction management theory, it is necessary to promote and extract, step by step, the principles of thinking, the substantial concepts, the fundamental rules, and the scientific questions derived from mega infrastructure construction management practices, to reflect on the essential ideas of theoretical thinking and to then establish a multilayered logical relevance among them. This is the formation path for mega infrastructure construction management theory.*

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4.1 Complexity: The Principles of Thinking (Mega Infrastructure Construction Management Theory)

Just as the first step regarding a mega infrastructure construction project is to create a top-down design, so too is the first step in the development of a mega infrastructure construction management theory (Tian 2014), though the top-down design for the development of the theory is to decide the principles of thinking with respect to that theory.

To decide the principles of thinking of mega infrastructure construction management theory is to specify the essential attributes of mega infrastructure construction management questions and to form a correct understanding of the related theoretic questions (Xu 2001). Because developing a mega infrastructure construction management theory is an endeavor that falls under the category of theoretical thinking, only through theoretical thinking can one grasp the essential attributes of the research object and attain the highest levels of knowledge, i.e., rational knowledge. Since theoretical thinking involves knowledge of the essential attributes of the research object and since our research object is mega infrastructure construction management, we must identify the essential attributes of the object.

As acknowledged, mega infrastructure construction management knowledge is the result of the contemplation of solutions to various phenomena and problems in mega infrastructure construction management practices. With respect to management activities of the same content and management problems of the same nature, construction thinking assumes different forms and displays different degrees of application in different specific management activities. Thus, there is no possibility that construction thinking can remain uniform. Theoretical thinking, however, is different. Because theories primarily explore and search for sameness, universality, and regularity of basic scientific questions within a field, theories must make generalizations about various specific phenomena and problems. That said, only by making abstractions can mega infrastructure construction management theory reveal its qualities, functions, and values through concepts, fundamental principles, and scientific questions. However, abstractions are often made at the cost of the uniqueness and specific characteristics of specific problems. Thus, though theoretic studies are generally conducted in certain ideal situations, it should be noted that the idealization of situations must have a basis. Consider, for example, mega infrastructure construction management theory where mega infrastructure construction management activities are of a practical type that organize and coordinate people to construct and utilize a project. For any stable practical type of activity, there is actually a rule or prescription for that activity, that is, a cognitive standard that distinguishes one type of activity from all the other types (Kerzner 2013). Theoretical research only uses this standard to make abstractions about related problems and to then develop basic theoretical elements.

The question then arises: What is the cognitive standard for mega infrastructure construction management theory?

We noted in Sect. 2.3 that complexity is the essential attribute of mega infrastructure construction management activities, phenomena, and questions (Wang and Cheng 2009). This suggests that although specific mega infrastructure construction management activities, phenomena, and questions are various and different from one another, we can make generalizations about scientific ideas in accordance with the principles of system science. For example, as mega infrastructure construction management activities are, in essence, a type of complex system, their sameness, universality, and regularity in the sense of complexity can be determined by analyzing the system's elements, relevance, structure, functions, and behavior. In other words, despite the differences in specific mega infrastructure construction management phenomena and questions, their common root, which is complexity, can still be found. On that basis, the theoretical principles of thinking can be established *to study mega* infrastructure *construction management questions from a general perspective where the first and primary focus should be on their common root of complexity to reveal the pattern of the questions based on that root*. As for the research of specific management questions related to a specific project, this research can be conducted after the root has been identified and understood clearly. Then, based on that understanding, an individual study can be conducted that considers such factors as the question's surroundings, characteristics, and specific details.

In short, having specified the principles of thinking with respect to mega infrastructure construction management theory means that we have established our understanding of the theoretical research of mega infrastructure construction management. Thus, regardless of the specific forms of the research questions in mega infrastructure construction management theory, the essential attributes of the questions can be concluded under the category of complex systems. In this way, the logical system and discourse system of system science will provide tremendous support for the establishment of our research approaches and guarantee the normativeness of our study. In addition, consistency between knowledge and methods is required by principles of thinking. As for the principles of thinking of complexity, scholars have established initial corresponding methodological principles and systems after decades of research (Giezen 2012; Salet et al. 2013; Yan et al. 2009; Jin 2001), which gives us every reason to employ those principles and design the technical path for the theory. A detailed discussion of this is presented in Part 4 *Methodology System of Theoretical Research on Mega Infrastructure Construction*.

4.2 Core Concepts: Discourse Basis of Theories

Language is not only an important tool used by people to express themselves and communicate with others but also a tool used for thinking. People use language to express the process and results of their thinking (Mercer 2000). In everyday life, people think and communicate using natural language, but the plainness of natural language makes it difficult for the language to express, convey, and communicate the attributes or nature of an object or to accommodate an abstraction people have about the attributes of the object. In other words, language stops at the stage of describing the superficial appearance of phenomena and relations. Especially, as theories are the results of theoretical thinking, with natural language as the basis, special scientific language is also needed to accurately define and thoroughly explain the nature of a field that the theories represent. Thus, the basis for scientific language in theories is concept (Kuhn 1979). *Every concept is a generalization that people make about the essential attribute of an object, and as such, it is an abstract condensed expression of the nature of, and inherent relations within, that object*. For this reason, concepts enable people to improve their thinking ability and to evolve from the concrete level to the abstract level, and they serve as tools for members in scientific communities to communicate. Accordingly, concepts constitute theoretical and scientific discourses.

Concepts are expressed in scientific terms. Basic concepts in mega infrastructure construction management theory are abstractions of the attributes of mega infrastructure construction management practices based on the repeated cognition of primary phenomena and behavior in those activities and are, accordingly, logical reflections of the attributes of management activities. Concepts not only include people's knowledge of the essential attribute of construction management by means of construction thinking and theoretical thinking but also reflect the logic through which the attribute forms. Thus, concepts serve as the basic elements for theories (Wu 2005).

It is especially true that proposing concepts that reflect the essential attributes of mega infrastructure construction management theory during the theory's developmental stage to tackle questions that are still unclear contributes to finding the answers to those questions. Since it is concepts of a new theory that are being proposed, caution should be taken during the process to ensure that the concepts are connected to the practices, that they reflect essential attributes of the practices, and that they exhibit theoretical value. During the development of a new theory, it cannot be avoided that ordinary language may often be used in the beginning to express concepts. This is acceptable and often facilitates the understanding of a phenomenon and its nature. This situation, however, should occur as little as possible, and the expressions should be as brief as possible because it would otherwise influence and hurt the accuracy, profoundness, and rigor of our theoretical thinking. Therefore, to improve our understanding of phenomena and their patterns, it is necessary for us to raise the level of the concepts proposed to a level where the concepts are, to some extent, descriptive and contribute to the generalization of logical connections inherent to the phenomenon.

It is further noted that the fact that system complexity is the essential attribute of mega infrastructure construction management does not mean that concepts of a complex system theory can be directly adopted as mega infrastructure construction management theory. This is because, as abstractions of basic attributes of overall phenomena and questions in natural science, social science, arts, and humanities, complex system concepts are more general and basic (Wu 2005). Therefore, the direct application of those concepts to mega infrastructure construction management could only yield general concepts. General concepts, as one of the knowledge domains that present an overall understanding of an object, can serve as the framework for mega infrastructure construction management theory, but the lack of uniqueness with respect to mega infrastructure construction management activities will undoubtedly lead to a list of concepts that are separated from concrete and lively management phenomena and scenarios and finally end up as lifeless labels, which may help with everything but the development of mega infrastructure construction management theory.

Therefore, though we have decided that system complexity is interpreted as the principles of thinking for mega infrastructure construction management theory, the concepts of complex systems theory should not be directly applied as concepts for mega infrastructure construction management theory. Instead, we must extract *substantial concepts* that represent a thorough reflection of both the form and the nature of mega infrastructure construction management practices based on management activities.

Proposing concepts is a fundamental function when developing mega infrastructure construction management theory. Good concepts not only improve the systematic and logical qualities of a theory, and thus contribute to the acceleration of the theory's development, but also help us to observe and understand the nature of mega infrastructure construction management.

The better the concepts reflect the essential attributes of mega infrastructure construction management, the more fundamental and substantial those concepts are for mega infrastructure construction management theory. Thus, the number of concepts should be relatively low, as they are the essence of the concept system. *Just as in the principle of Occam's razor, the theory requiring the fewest assumptions is most likely to be the most accurate* (Rasmussen and Ghahramani 2001).

To be specific, during the development of mega infrastructure construction management theory, we may first develop general categories between mega infrastructure construction management and complex system science, such as a mega infrastructure construction-environment compound system, system complexity, etc., through inductive and deductive methodologies. However, the categories are, for the most part, general descriptions of mega infrastructure construction management and philosophical inspirations that lead us to determine which modes of thinking should be employed to understand mega infrastructure construction management and to help us outline the thinking framework for our cognition of mega infrastructure construction management. Categories, however, are not clear scientific terms that we can use to describe the essential attributes of mega infrastructure construction management, as they do not reach the level necessary, as theoretical elements do, to be developed into fundamental principles and scientific questions. Therefore, we must develop a system of concepts for mega infrastructure construction management theory. Logical connections among these concepts should be ensured such that a classification of the concepts can be created based on the connections (Walker 2015). For example, concepts for mega infrastructure construction management theory can be divided, based on the nature of the system elements of construction management, into basic (core) concepts, management subject concepts, management objectives, management organization, management problems, management environment, etc. Though there is, of course, more than one way to classify concepts, such classification is helpful for the insertion of the element of management, i.e., its attribute and significance, into concepts and for the easy presentation of mega infrastructure construction management questions through the reorganization of concept. Such classification and organization result in questions revealing themselves in a clear structure with cause and effect details (Forsberg et al. 2005).

It is through these concepts and through the system of discourses, all of which are clear, explicit, and accurate, that theories are conceived as they evolve along different dimensions with concepts as the starting point. Accordingly, developing a system of concepts is the first step toward a mega infrastructure construction management theory.

4.3 Fundamental Principle: The Critical Thinking of Theory

Once the concepts have been defined, they serve as the foundation for the development of the theory. Thus, they can be combined in such a way that they can be used to analyze mega infrastructure construction management phenomena, in the hope that reasonable explanations for the logical relations, cause-effect relations, or other relations present in the phenomena can be identified, and, in the process, the basic rules and premises behind these phenomena can be extracted, which then allows for the formation of a conclusion. Accordingly, this statement will constitute the fundamental basis of a theory system (Wu and Du 2001). From this fundamental basis, we can determine derivations, provide explanations, and make predictions about general questions and phenomena with respect to the mega infrastructure construction management activities. *A principle is one comparatively independent unit of knowledge that represents a basic understanding of the principles behind the behaviors and operations employed to address a certain task as well as an understanding of the phenomena in mega infrastructure construction management activities. Principles are often expressed as affirmative judgments.*

The fundamental principles of a theory are important because the basic and formalized rules behind them can facilitate an accurate and deep understanding, beyond that at the concept level, of the essence of mega infrastructure construction management activities. Moreover, they can help to determine the rules of behaviors and operations at the practical level.

In contrast, some principles are more fundamental and more original than others and may have beginnings that date back to a much earlier stage. Furthermore, the statements they express not only generalize the basic pattern of phenomena under a certain category but also provide guidance for multiple types of phenomena and questions as well as for theoretical thinking, which is of overall importance. In this sense, principles can be used to directly deduce theoretic conclusions and to develop new principles. *Thus, they are called fundamental principles.*

Fundamental principles are often expressed as affirmative statements and rules given a certain condition. Accordingly, fundamental principles indicate that the theory system has the function of logical deduction. The logical deduction function is actually the meta function of a theory. That is, the fundamental principles can be used to deduce new specific theoretic units that are affirmative in nature, and these theoretic units can further be used at a higher level to form scientific questions.

As the mega infrastructure construction management theory is designed and developed within the combination of natural science, social science, humanities, and engineering technology (He and Wang 2008), the theory is natural, social, and humane. Being natural indicates that the theory has features such as objectivity, as in the rules of nature, and normality, as in technological operations; being social suggests that the social environment is closely related to the constructions and subjects of construction management and that it also considers the subjects' preferences, profits, etc., and being humane refers to the subjects' psychology, vision, cultural values, etc. *It is because of these three features, i.e., natural, social, and humane, that the fundamental principles of the mega infrastructure construction management theory cannot be treated as those in natural science, i.e., they cannot be condensed into signs, formulas, or axioms but should be, in most cases, expressed as principles for relations and rules for behaviors given a specific circumstance* (He and Wang 2008; Jin 2001).

We consider complexity, the essential attribute of mega infrastructure construction management, as an example. The core of mega infrastructure construction management theory and practical behavior management is to know, analyze, and master this attribute. Specifically, the process to accomplish this includes extracting various complex phenomena and classifying their subtypes and decomposing the complexity with the support of behavioral principles and operational rules based on a respect for the objective complexity of constructions and construction management (Xu et al. 2008). Given that the process of understanding management complexity is complex in itself, it is necessary to first propose corresponding fundamental principles for each of the following: the constitution of management subjects, the behavioral norm of the subjects, the organizational mechanism, especially the match of the organizational mode with management complexity, etc.

In addition to classifying the elements of management questions and management activities, a series of behavioral principles should be summarized and suggested to establish orderly and effective management activities and behavioral operations. To achieve this, we must first build the foundation for the decomposition of complexity with respect to the mega infrastructure construction management activities and then propose a multi-scale management plan based on multi-scale management phenomena, that is, an adaptation selection scheme to cope with the changes in management scenarios and other fundamental principles. As has been proven in practices, these fundamental principles are the basic source for the development of a mega infrastructure construction management theory.

4.4 Scientific Questions: Core Ideas of a Theory

The scientific questions of a theory system are types of questions described in concepts and derived from fundamental principles. As such, the questions are of high academic quality and theoretical value. Scientific questions should not be confused with specific practical problems in mega infrastructure construction management activities because researching and solving specific practical problems fall within the field of construction thinking, while researching scientific questions, i.e., extracting and abstracting the basic structure and essential attributes of a large number of specific management questions of the same kind, is a matter of theoretical thinking.

More specifically, for a certain construction management question, construction thinking is first employed to describe, clearly and in great detail, the background, environment, tasks related to the question, and expectations of the subjects, whereas corresponding theoretical thinking is then employed to analyze the question so a detailed solution can be proposed. Scientific questions, however, aim at clearly describing the elements, structure, correlations of a certain type of question/problem, and the common features and patterns of the environment and the scenarios. Then, based on the nature of the questions, prominence is given either to the rationale behind the questions, i.e., what and why questions, to the process of the questions, i.e., forecasting how the questions will evolve, or to the scenarios of the questions, i.e., unveiling the characteristics of how the questions will change over a period of time or as the result of a change in location. Scientific questions tend to be more concerned with the technical path and methodology, which are guided by theoretical thinking, than with detailed solutions. In fact, no detailed solutions can be proposed in this case because, under the auspices of theoretical thinking, studies of scientific questions require erasing any trace of the particularities and uniqueness of specific questions and maintaining the elements and structures of the related questions, which can then be expanded, renewed, and reorganized. Such are the key differences between the scientific questions of mega infrastructure construction management theory and the practical questions related to specific construction activities.

For example, one of the scientific questions mentioned in later chapters, deep uncertainty decision, does not refer to a certain decision that must be made regarding either a certain construction activity or a mega infrastructure construction management theory, such as the site, scale, or investment model for a construction activity. Rather, it is the common feature extracted from those issues. This is because if the specific background of those issues and the attributes of their elements are removed from focus and only their essential attributes are extracted, it will be revealed that deep uncertainty decision is one of the scientific natures of a large number of complex decisions related to mega infrastructure construction management. Researching this scientific question, explaining its core phenomena using theoretical thinking, and unveiling its basic patterns will guide people in their decision-making processes regarding mega infrastructure construction activities.

Similarly, other scientific questions undergo comparable procedures and have similar significance. This is the allure of the scientific questions about a theory.

The number of important scientific questions reflects the strength of the theory. The greater the number of questions is, the stronger the need to construct the theory and the greater the academic value and guiding significance of the theory system.

Core scientific questions regarding a theory refer to questions that are fundamental, basic, and sound. These questions often are highly extracted descriptions of management functions and are characterized by universality. Therefore, the more the scientific questions address practical management functions, the more mature the theory is.

Scientific questions of mega infrastructure construction management theory are generally expressed as abstract questions regarding a certain management task, or they are universal questions that must be finalized within a certain scenario. Scientific questions require conciseness, but at the same time, they command a room as large as possible for expansion, as additional scientific questions may arise from the core scientific questions. Scientific questions are of great importance to a theory not only because the explanations, predictions, and guiding functions of a theory for practices are realized primarily through solutions to scientific questions but also because, within the logical framework of a theory, new scientific questions grow out of the old questions through combination or reorganization or as the result of examining a question at a deeper level. In other words, scientific questions are seeds that can organize themselves and grow into configurations that lead to much richer questions regarding mega infrastructure construction management theory.

According to the general pattern of forming a theory, it is evident that under the guidance of the principles of thinking about complexity and after going through the four stages, namely, determining the principles of thinking, building the system of concepts, forming the fundamental principles, and extracting the scientific questions, the path of building a standard and complete mega infrastructure construction management theory is formed. That said, the four-stage theory-forming path is still at the macro level, and thus, it is a task without delicate attention to detail. A much more difficult task is to design and extract the concepts, fundamental principles, and scientific questions with respect to the theory system, a task that determines the scientific and academic quality of the theory.

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Main Themes in Part 2

Mega infrastructure construction management theory refers to the theoretical system that can explain the phenomenon of mega infrastructure construction management, can reveal the general rules for management activities, and can guide practice. This theoretical system should not only involve conceptual systems that offer basic principles, scientific problems, and profound insights into essential attributes of the specific field but also provide corresponding methodologies. Accordingly, it is the integration of systematic and logical knowledge about mega infrastructure construction management.

With respect to the practice of management activities, the common way of thinking to determine what construction management is and why it was established is called theoretical thinking. Constructional thinking, which focuses on transforming constructional models into reality, involves planning and implementation as its primary missions and, thus, specifies "what to do" and "how to do."

Mega infrastructure construction management activities involve, simultaneously, both theoretical and constructional thinking along with any other thoughts. However, mega infrastructure construction management theory is primarily the result of theoretical thinking.

For the past several decades, the construction field has been dominated by the project management system. The project management knowledge system is a system of knowledge and skills that is characterized primarily by construction thinking and provides guidance regarding "what to do" and "how to do" in management activities. Beginning with the scientific connotation and fundamental principles of the theoretical system, the PMBOK should not be defined as a construction management theory system that is based on theoretical thinking, nor should it be regarded as being decentralized due to its systematic and logical attributes.

Given the framework of the academic ideology adopted herein, mega infrastructure construction management theory, mega infrastructure construction management theory system, and mega infrastructure construction management basic theory are regarded as synonymous in that their connotations are essentially the same.

To date, a standardized and developed mega infrastructure construction theory system has not been established, though its construction is in its embryonic phase.

The establishment of a management theory is currently a complicated knowledge system construction that develops from nothing. Its core missions are to adhere to the general rules regarding the formation of a theoretical system that is based on theoretical elements and logic relations to design a structured theoretical system.

This process should be conducted under the system complexity's principles of thinking. Certain issues must be investigated at the same time, including the identification of the core theoretical elements and concepts and the basic principles that can be proposed through logical judgment. Furthermore, the process should be able to extract the abstract statements regarding the functions of management, that is, to formulate fundamental scientific problems. Though each step in the process is relatively independent, it is also closely interconnected with respect to logic. Ultimately, an integrated framework of the theoretical system can be completed by following the procedures within the theoretical domain, namely, principles of thinking, substantial concepts, basic principles, and scientific problems. Accordingly, to establish a mega infrastructure construction management theory, subjects should propose principles of thinking, substantial concepts, basic principles, and scientific problems, all of which come from management practice and embody the content of theoretical thinking. Meanwhile, their mutual multilayered logic associations should also be constructed. In conclusion, all of the above comprise the whole of the standardized technological approaches necessary for the development of a theory.

Part III
The Core Scientific Connotation of Mega Infrastructure Construction Management Theory

This section, which is composed of three chapters, is the core of the book. As such, it focuses on the details regarding the concepts, principles, and scientific problems addressed in the mega infrastructure construction management theory. Additionally, governed by the principle of thinking with respect to complexity, this book also attempts to conduct a standardized exploration of the formation process of the mega infrastructure construction management theory.

The practical activities of human beings with respect to mega infrastructure construction management are infinitely abundant and ever accelerating. Accordingly, no one theory makes it possible to resolve all of the theoretical problems under certain specific historical periods and conditions. Rather, theories are developed, innovated, and implemented with practice. Thus, present theories are enhanced as well.

It is acknowledged that everyone's observations and experiences regarding the practical activities of mega infrastructure construction management, as well as their considerations of the theory, are both partial and limited, as individuals can only perceive these activities from certain perspectives. Even if they attempted to avoid their personal cognitive bias, the mega infrastructure construction management theory they construct would be inevitably incomplete and deficient.

On the one hand, the mega infrastructure construction management theory reflects the universal truth behind construction management. This truth is concluded through the theoretical thinking of individuals. On the other hand, however, to be more sufficient and effective, this truth must be supplemented and improved. In fact, these are the universal phenomena and rules during the course of advancing theories within the realm of science.

Thus, in the early stage of the present construction, the area of construction management should embrace scholars from all over the world and encourage them to actively explore and study the mega infrastructure construction management theory. China's valuable historical experience and its impact on academic prosperity and development is best expressed through the statement, "let a hundred flowers blossom and a hundred schools of thought contend," a phrase that should be regarded as the common principle that propels the research on the mega infrastructure construction management theory.

Accordingly, in the latter part of this book, the proposal regarding concrete research on management theory is an exclusive perspective in the overall sense, a partial theoretical achievement of a particular group of people in a specific period based on management practice, a consideration based on the practice of theory, and a contribution to the advancement of construction management science made by construction managers in China. However, the numerous statements and various types of theoretical achievements reported by various countries make the theoretical system much more complete, profound, and powerful. Hence, viewed from the perspective of the advancement of a theory over time, to establish mega infrastructure construction management theory would always be advancing. In fact, theory advancement is considered the norm during the process of developing any scientific theory.

Chapter 5
Basic Concepts of Mega Infrastructure Construction Management Theory

Beginning with the practice of mega infrastructure construction management activities, this chapter proposes certain basic concepts within the system of the theory. The thinking principles and cognitive depth of researchers with respect to management theory are reflected in the concepts they propose and the logic relations among those concepts.

5.1 Basic Concepts in Mega Infrastructure Construction Management Theory

In this section, basic concepts of mega infrastructure construction management theory are introduced.

5.1.1 Mega Infrastructure Construction-Environment Compound System: An Objective Concept

Once the entity of mega infrastructure construction is established within the previous periphery of the construction districts, the mega infrastructure construction as a new system element is added to the original environmental system. In this way, with respect to the former environmental system and the newly established mega infrastructure construction, a new artificial system is created. *This new system is called the mega infrastructure construction-environment compound system.*

First, based on the previous environmental system, the new system has incorporated a new system element, namely, the mega infrastructure construction. As a consequence, all of its components and correlations between elements, as well as the structure and functions of the system, will undergo change. Then, apart from the

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economic system, the social system and ecosystem from the previous environment have enhanced the artificial mega infrastructure construction system. A complex pattern, e.g., a system of another system is presented, which we call the mega infrastructure construction-environment compound system.

This system has important theoretical implications with respect to the concept of the mega infrastructure construction-environment system in mega infrastructure construction management theory. Generally, mega infrastructure construction is designed and built to allow the mega infrastructure construction-environment system to perform a series of expected functions after establishing the foundation for mega infrastructure construction. However, in reality, except for the possibility of realizing those expected functions when the construction was designed, the occasion where the new compound system would be unable to achieve those functions may also occur. Moreover, some completely unanticipated and unexpected functions could possibly arise as a manifestation of the functional evolution and emergence of phenomena regarding this system. Moreover, the reality indicates that among those evolutionary and emergent functions, it is probable that there are some functions that will negatively affect the society and the environment, thus creating new problems that the mega infrastructure construction management theory must study and prevent.

For example, the Three Gorges Project (TGP), which is located in the city of Yichang in Hubei Province and Chongqing city with the Yangtze River in between, is the largest hydropower station in the world and also the largest water resource and hydropower project constructed in China. The TGP has many functions, including shipping, power generation, and flood control. After its establishment, the TGP and the huge upstream area of the Yangtze River formed a new compound system. Over time, however, the structure and the functions of this compound system have undergone new and significant changes that have caused intense reactions to the TGP. At this moment, as the functions of the TGP become interwoven with the reactions of the compound system, many anticipated and designed phenomena may arise, and in return, certain opposite reactions never before anticipated are also to occur. This is because people's common sense often serves to know often overrides knowledge and predicts the direct phenomena of intuition, dominance and causality. However, the complex phenomena resulting from the compound system in a great space-time continuum usually have implicitness, conductivity, and variability, characteristics that are far beyond people's common experiences and knowledge capabilities. Therefore, it is impossible to propose an entire expectation and prediction during the engineering project argumentation.

A typical example is that in recent years, a large-scale reservoir construction was conducted in the main tributary channel of the Yangtze River, which lies in the upstream part of the TGP. Therefore, the phenomenon of the Great Leap Forward due to hydropower increased, an occurrence that has greatly changed the systematic structure of the TGP-environment compound system. The Jinsha River is another example. In 2002, the planning for the hydropower development of the middle Jinsha River was authorized. The plan is to build up to 25 hydropower dams along the river. It is to be a huge reservoir with one cascading reservoir every 100 km, on average. Some other rivers, such as the Minjiang River, Jialing River, and Wujiang

River, which are in the upstream part of the Yangtze River, have also been exploited. Furthermore, some fresh reservoir groups are also currently under construction. The intense hydropower development within the district of the TGP-environment compound system has objectively exerted sweeping influences on the TGP in many ways. For instance, the intercept of a multi-level cascade in the upstream portion of the Yangtze River has led to a sharp decrease in the sediment flux into the reservoir of the Three Gorges. Some experts have even predicted that after the construction of more reservoirs in the upstream area, the sediment flux into the reservoir of the Three Gorges would take up only 10% of that which was previously calculated. On the one hand, this reduced the impact of the sediment on the Three Gorges. On the other hand, however, it caused a new and unexpected problem, the release of clear water. The riverbed of the Yangtze River had experienced water erosion and been unceasingly deepened. This resulted in the drop of its water level. In the riparian zone of Hubei's Dongting Lake, part of the Yangtze River, the position of the bottom of its riverbed was even higher than the water level of the Yangtze River during the winter's low-water period. As the Yangtze River is not allowed to flow into the lake, the drought in the downriver lake area is further aggravated. "The relationship between Dongting Lake and Yangtze River has been established over the past ten thousands of years. However, now it was disrupted. The aquatic organisms could have entered into the lake, but they failed. The whole ecosystem is about to change" (Weng Lida, a speech given on the group of sediments in the TGP).

According to the results of sediment research conducted by the Yangtze River Water Resources Commission, during the 30 years after the impoundment of the Three Gorges Reservoir, without human intervention, the Jingjiang River reach of the Yangtze River will suffer from heavy water erosion. Over 70% of the erosion will occur in the lower reach of the Jingjiang River, and its riverbed will be deepened by approximately 7.4 m, on average. Based on the results reported by the Chinese Academy of Sciences, the lower reach of the Jingjiang River will be deepened by more than 10 m due to the 50 years of water erosion. In other words, the Three Gorges project-environment compound system has caused the juxtaposed phenomena of the positive action of construction and the reverse action of the compound system, whose consequences are severe.

From this example, it may be concluded that the idea of a mega infrastructure construction-environment compound system is of great significance for both the theoretical research and the practice of mega infrastructure construction management.

5.1.2 Complexity: The Objective, Subjective, and Environmental Concepts

In Sect. 2.3, we noted that from construction management to mega infrastructure construction management, the crucial change in the attributes is the transformation from systematicness (Hobday 1998; Shenhar and Dvir 1996, 2007; Shenhar 2001; Davies and Mackenzie 2014) to complexity. This conclusion is based on people's cognitive thinking, while the complexity in the present section is proposed as a basic concept in mega infrastructure construction management theory.

Complexity (Morris and Hough 1987; Miller and Lessard 2001; Flyvbjerg et al. 2003; Meier 2008; Söderlund 2012), as a basic concept, is the result of the abstraction and refinement of the objective essential attributes of mega infrastructure construction management objects as well as the internal relations of management activities. It ostensibly seems to be the statement of the discourse system of system science, but it is only borrowed from the system science language. Therefore, it is necessary to interpret the connotation of mega infrastructure construction management.

First, complexity should be interpreted as an integrated concept of mega infrastructure construction management theory. For example, it can be the physical complexity of construction, the systematic complexity of recognition, or the managing complexity of management activities. It can even be the synthesis of the complexity of several parties, such as the overall complexity of establishing mega infrastructure construction management.

Complexity is a concept that appears in several subjects. For example, in the fields of physics, chemistry, and biology, the concept of complexity has respective backgrounds and concrete meanings. Therefore, we should not define the complexity of mega infrastructure construction management by using the definitions applied in the fields of physics, chemistry, etc., as doing so would undermine the concept such that it would become empty and insipid and lack the practical significance required of mega infrastructure construction management.

Therefore, to provide a definition of the concept of complexity, the four aspects of mega infrastructure construction management activities are combined, and a description and abstraction of each of the four aspects' interpretation of complexity are presented.

1. *Complexity Originating from Social Economic Environment*

With its obvious social public nature, nations commonly invest in mega infrastructure construction. Meanwhile, market economic factors and rules (Geraldi and Adlbrecht 2007; Bosch et al. 2011) have been playing increasingly important roles in mega infrastructure construction. This sort of environment involving the participation of both the government and the market has profoundly affected many aspects of mega infrastructure construction management, and as a consequence, it has been misrepresented and distorted for many reasons. Among those reasons are the incomplete market-oriented economy of China, the imperfect regulations, the lack of qualified construction enterprises and project management companies in the construction market, the market information asymmetry and the massive existence of excessive government intervention in construction. For example, to give full play to the leading role of the government, a construction headquarters should be established in most cases. At the same time, as the legal entity, the project company, in accordance with the market-driven mechanism, must take charge of the funding of the construction and the management of the operations after completion. In this way, “a project simultaneously possessing both a construction headquarter and a project company” would be formed, which would increase the degree of complexity in the management and organization of the project.

The market economy is essentially open-ended. In pace with the opening-up of the labor and employment system in China, construction enterprises tend to recruit low-paid employees from the labor market and engage them in the construction as first-line workers. In general, the labor-capital relationship between these enterprises and migrant workers is so weak that it not only negatively impacts the stability of the entrepreneurs’ team development but also generates a huge gap between the workers’ real skill levels and the requisite skill levels of workers, thus contributing to the complexity of many aspects of mega infrastructure construction management.

2. *Complexity Originating from Multi-Agent Construction*

Apart from the government, mega infrastructure construction management subjects generally represent many entities, owners, planners, designers, supervisors, research and design institutions, contractors, suppliers, and other functional departments (Baccarini 1996; Williams 1999; Geraldi and Adlbrecht 2007; Vidal and Marle 2008). Such a group, on the one hand, greatly facilitates the synthetic ability of construction management resources. On the other hand, however, it has unavoidably shaped the co-existing pattern of multiple values and multiple benefits. It is also one of the reasons for the complexity of mega infrastructure construction management. Most importantly, with respect to mega infrastructure construction management, the government represents the public’s value orientation, while contractors and suppliers have not only their own respective interests but also many complex contradictions under the economic system of the market. Thus, there may be some sharp conflicts, and acts of alienation may occur. In a market environment, these problems should not be simply criticized or dealt with morally; rather, it is necessary to design and implement an effective management system that, by virtue of laws and contracts, regulates subjects’ behaviors, resolves conflicts, and achieves a win-win result. Again, the actions will increase the complexity of management.

3. *Complexity Originating from Deficient Synthetic Ability of Subject Resources*

A project is an activity that is conducted through resource integration. Therefore, the resource integration capability of construction subjects should be a crucial sign of excellent construction management ability. During the course of mega infrastructure construction management, subjects will generally encounter two challenges regarding resource integration capability.

1. On some occasions, though construction subjects have access to necessary construction resources, resource integration is often difficult to realize, for example, when integrating administrative resources with market resources, combining construction data resources with experts’ experiences and wisdom, or uniting subjects’ imagery thinking with logical thinking to form innovative thinking. Furthermore, there exist complex negotiating processes, such as those between

government departments, between the government and enterprises, between enterprises, and between individuals. As for the related integration methods, many, such as quantitative methods and professional experiences, rationality, and perception and qualitative methods and quantitative methods, are characterized by a complicated design and require analysis.

2. In other situations, if construction subjects have no access to complete construction resources, their top priority is to gain access to unavailable resources and to then manage the resource integration, which could involve resources with varied properties. When the resource is the construction fund, the owner should design a specific proposal, determine the ratio structures of various types of funds, develop capital investment plans according to investment and finance policies, and even expressly establish a legal institution to manage issues related to planning, finance, operations, and debt refunding, which inevitably would increase the complexity of the construction management organization. When the resource is key technology in construction and the contractor is not equipped with the independent technological innovative ability, an owner-led technology innovation platform should be established that includes cultivating the construction enterprise to become the technovation subject, thus representing a breakthrough in key technology. This process involves planning the strategy for science and technology with respect to construction and designing the innovation platform and platform configuration, all of which, again, contribute to the complexity of construction management.

4. *Complexity Originating from the Integration of Construction*

Mega infrastructure construction involves not just the integration of hard resource, such as materials, equipment, and technologies (Bosch et al. 2011), but also the integration of soft resources such as information, organization, and management. Therefore, the integrated level between each part of construction must be significantly improved, and their transverse influences and interactions must be far more radical. Furthermore, even the previous local effects may evolve into overall influences that are capable of dominating the entire construction. The preliminary development planning and feasibility studies regarding mega infrastructure construction indicate that total predictability with respect to mega infrastructure construction is not possible given such complex associations. Meanwhile, the previous seemingly simple and direct causal relationships formed during construction may become blurred.

The high level of integration between each part of mega infrastructure construction usually results in small local changes or errors being magnified into serious overall accidents. Thus, a level of integration not only makes the construction risk more unpredictable and emergent but also makes the analysis of the risk source more difficult to conduct. At construction sites, many conventional methods of quality control and safety management would likely be inefficient and result in little effect, and due to the invisible causal relationship among construction factors, the customary normal management procedures and measures would become the valve that opens the way to construction accidents. Hence, more serious accidents would occur.

In addition, during the process of construction, the final target of establishing a complete construction entity is often divided into many stages and sections on which different subjects work independently. Accordingly, there must exist a series of artificial connects with incomplete and asymmetric information while the construction entity is being built. Even if all the subjects are rational and well-intentioned, this does not ensure that the final results of all of their rational and well-intentioned behaviors will benefit the construction management. Because mega infrastructure construction is a complex system, incomplete and asymmetric information is not an avoidable phenomenon.

To help minimize problems, we may employ certain reinforced remedial measures. For example, to improve the stability of construction components, we may take some measures to strengthen their interconnections. This not only is feasible but also optimizes the issue of reinforcing the local structures of construction. That said, however, such methods aimed at promoting local stability may weaken the construction itself when managing small amounts of turbulence. As an invisible accident, such vulnerability may become the incentive for destruction due to an external incidental influence. Moreover, a vulnerability may create a chain reaction within a highly integrated project and ultimately cause huge accidents to occur. This, in fact, leads to a new question that is posed due to the complexity of mega infrastructure construction. To create a mega infrastructure construction entity that is more stable within the environment, administrators tend to strengthen the association of construction structures. However, this may unavoidably increase the systematic complexity of the construction, thus causing the construction to be more vulnerable when managing small amounts of turbulence. This suggests that the high integration of a mega infrastructure construction could result in a clash between the stability of the construction and its vulnerability.

Similarly, to overcome the difficulties in safety management with respect to mega infrastructure construction, administrators should exploit the advanced information technology and computer systems. Through the human-machine compound system, the quality of safety management could be improved. Nonetheless, once any part of the system breaks down or any human error occurs, the functions of the system similarly break down. That is, at this point, the reliability of the safety management system plummets, indicating that there is an inverse relationship between the safety of mega infrastructure construction and its systematic reliability. Accordingly, it is deduced that the high integration of mega infrastructure constructions produces a series of new complex features.

In conclusion, at the very least, we can now emotionally realize the background and the meaning of complex management with respect to the many aspects of the practical activities involved in mega infrastructure construction management. However, it is also necessary to further generalize the concept and draw abstractions based on its foundation.

1. *As management complexity is intuitively difficult, confusion may be experienced by subjects during the management activities of mega infrastructure construction. For example, when confronted with a problem, subjects find it difficult to*

state clearly, analyze thoroughly, or predict accurately the problem and may find it impossible to propose a solution or resolution to the problem. This inability is the result of complex sensitive cognition. If the sensitive cognition is abstracted into an attribute on the rational cognitive level, it can be perceived as management complexity.

2. There are several reasons or causes that contribute to management complexity such as the objective environment, the inherent attributes of phenomena and problems, or the lack of subjective abilities of subjects. Though we cannot list all of the possible reasons, the more common ones include the serious uncertainty about the construction environment, the multiple management subjects, the numerous elements involved in management problems, the strong correlations among elements, and the diversity regarding the relationships among the numerous elements.
3. Regardless of the reason, however, management complexity poses difficulties for mega infrastructure construction management activities and becomes a major stumbling block that interferes with construction and management. Thus, new methods are necessary to contend with management complexity, as the failure to do so could result in the failure of the mega infrastructure construction project or could seriously negatively impact the quality of the construction quality.

The significance of mentioning management complexity with respect to the mega infrastructure construction theory system lies in the following:

1. By classifying and analyzing management complexity, we are able to sort the complex problems in mega infrastructure construction management. These problems are the key difficult points that must be resolved as part of the construction management activities. Once this group of problems is resolved, all remaining problems related to the mega infrastructure construction management can also be resolved.
2. Analyzing different types of complex issues favors the selection of different targeted solutions. Not doing so would make it increasingly more difficult to find solutions when facing a situation where complex problems are chaotically unorganized.

5.1.3 Deep Uncertainty: Environmental and Subjective Concepts

Uncertainty (Knight 1964; Lawrence and Lorsch 1967; Head 1967; Chapman and Ward 2004) is a term commonly found in management studies. Whether it is decision-making, prediction, optimization, or human behavior studies, people encounter situations related to the environment, causal relationships, and behavior choices where they are not sure what to do. That is, they experience uncertainty.

Studies on uncertainty in management have not only acknowledged a respect for the general principles of management problems but also reflected human progress in the cognition regarding the essence of these principles. Initially, people preferred to describe and conclude phenomena and problems using the affirmative and incontestable causal certainty and inevitability. The reason for this is that by so doing, it is easier to conduct research, and the conclusion is explicitly clear. However, the increasing phenomenon of uncertainty in management activities revealed that, to some extent, the essence of management itself is uncertain, and as a consequence, many principles in management can only be described using the language of uncertainty. Uncertainty is an objective attribute, and since the time when the concept of uncertainty was proposed, people have come to realize that its counterparty, certainty, is a rare assumption. People have come to expect the uncertainty in management problems, and thus, they continue to explore management methods that can control for uncertainty.

Today, a consensus has been reached regarding the reasons for uncertainty in management. In general, there are two types of primary causes of uncertainty, as follows:

1. People cannot provide a unique and certain description, prediction, or judgment regarding the facts, states, or trends of a phenomenon or of future scenarios due to the inadequacy of their cognitive ability and the lack of information. This is generally referred to as *subjective uncertainty*. Along with the improvement of people's cognitive ability and their access to complete information, people's subjective uncertainty with respect to the management problem will decline.
2. A certain type of objective dynamic mechanism exists in management problems and related phenomena such that the states and operation results of problems and phenomena have many possibilities. This is referred to as *objective uncertainty*. Objective uncertainty has nothing to do with an individual's subjective cognitive ability. Rather, it is a type of objective attribute of objects and phenomena. Accordingly, unless changes occur in the structures and mechanisms of the facts and the phenomena, the uncertainty would either be changed or be reversed and thus disappear.

The uncertainty in management activities and phenomena incorporates not only subjective uncertainty but also objective uncertainty. On many occasions, these two types of uncertainty coexist and are combined with each other so as to form our entire cognition of uncertainty.

It was further found that in management practice, uncertainty has a degree of discrepancy. Therefore, for convenience, we might classify the uncertainty as either general or severe.

General uncertainty suggests the following:

1. The subject is clear about the type of problems and phenomena that he cannot, with certainty, affirmatively describe, predict, and assess and also knows the methods that can increase his level of certainty and decrease his subjective uncertainty.

2. The objective uncertainty of problems is the inherent attribute of the problems. Thus, the objective uncertainty does not change as a result of people's subjective desires. However, through prediction and statistics, people have acknowledged that their objective uncertainty does exist and that it follows some type of principle of certainty. Conversely, it is just this type of principle of certainty that weakens the inherent uncertainty. For example, the uncertainty in problems obeys a certain probability distribution and meets the fuzzy membership function and rough set confidence level. In this way, objective uncertainty will be either reduced or alleviated.

Not all uncertainty, however, is that easy to manage, as there are situations that can be far more serious. Before concluding a discussion of uncertain concepts, we examine how the severe uncertainty was formed from the following concrete phenomena and contexts of mega infrastructure construction management activities.

1. *Serious Uncertainty Formed by the Natural Environment of Mega Infrastructure Construction*

Mega infrastructure construction is generally located along rivers, seas, and mountains. An increasing number of projects consist of cluster projects, such as river and sea tunnels and artificial islands. In these areas, the hydrogeological conditions are complicated, the weather conditions are unfavorable, and local natural disasters are not uncommon. An example is the Qinghai-Tibet Railway, which crosses the mountains at elevations that reach 5072 m. One of the tunnels is 4767 m above sea level and 1686 m in length with an alpine hypoxia area along the railway, a fragile ecological environment, and active crustal movement. When establishing mega infrastructure construction in such a dangerous area, not only is there a lack of adequate relevant information and data regarding the natural environment and phenomena, but little is also known about the fundamental principles of the problems.

2. *The Severe Uncertainty Formed by the Social Economic Environment of Mega Infrastructure Construction*

Ordinarily, mega infrastructure construction is concerned with national well-being, people's livelihoods, social development, and national security. Therefore, it involves many areas and parties and is characterized by a degree of social concern. Accordingly, to engage public participation, expert argumentation, risk assessment, legitimate reviews, and brainstorming in the legal procedures of mega infrastructure construction during the decision-making process, it is necessary to improve the mechanism of making decisions in accordance with the law. At times, however, this legal environment is deficient or imperfect.

The Hong Kong-Zhuhai-Macao Bridge in China is a cross-border cluster traffic engineering project that was constructed by a joint effort of China's Guangdong Province, the Hong Kong Special Administrative Region, and the Macao Special Administrative Region. The early decision-making stage of a project and decision-making management are necessary to establish public power regarding administration, to create a clear legal environment, and to determine a consultation and dispute arbitration mechanism when determining common ground for the legal environment of mega infrastructure construction. However, due to the differences in laws, the administrative and engineering construction processes lead to severe deficiencies in the legal foundation. This situation was the first mega infrastructure construction case not just in China but in the world. Hence, we must first alter the current uncertain situation where the common foundation of the legal environment is severely deficient and establish a certain and stable social and legal environmental foundation for construction management.

In addition, mega infrastructure construction is built to provide welfare for the society and the public. However, during the construction, a conflict of interest with the public could possibly arise in local areas and cause local problems. For example, hydraulic construction projects generally require the relocation of a portion of residents living in the reservoir area, whereas mega hydraulic construction projects require the relocation of a large number of residents. In all, 1.4 million people have been relocated to make way for the TGP over its 18-year construction period. The construction of the Danjiangkou Reservoir in Hubei Province, which is an important component of the middle line of the South-to-North Water Transfer Project, required the resettlement of 330,000 people, a project that involved immigration resettlement planning; the design and implementation of a resettlement program; the providing of employment, education, and social insurance for the immigrants; and a plan to guarantee the stabilization of the immigration resettlement. This program obviously covered many areas and had a long activity chain that impacted the immediate interests of hundreds of thousands of people. Many stages were dynamic and experienced multiple modifications. Such a large-scale resettlement project was not only influential and difficult but also consisted of serious uncertainty with respect to social engineering that was composed of many uncertain elements.

Furthermore, mega infrastructure construction is a type of construction that requires a huge financial investment and includes, simultaneously, social and public attributes along with commodity attributes. Therefore, investment and finance policies of mega infrastructure construction must be introduced based on their distinguishing attributes. From a theoretical perspective, mega infrastructure construction has a feasible diversified pattern of investment and financing that is manifested as government investment, owner development, and society financing combined with the introduction of foreign capital. During the reinforcement period, however, this policy choice would inevitably concern a series of decision-making elements related to investment and financing, such as national politics, social stability, economic trends, financial stabilization mechanisms, public confidence, and the national monetary policy. Other elements include construction programs, the amount of static investment, control of project dynamic investments, budgetary estimate adjustments, policy support for immigration and demolition, and compensatory tax relief. All uncertain influences and the chances of the occurrence of the amplification of small risk factors in these stages are all likely to become sources of serious uncertainty with respect to the investment in and financing of mega infrastructure construction.

This indicates that various types of complexity with respect to the social economic environment have a critical effect on and can cause serious uncertainty in mega infrastructure construction management.

3. *Serious Uncertainty Caused by Large-Scale Evolution of Mega Infrastructure Construction*

If we comprehend the environment of mega infrastructure construction based on a greater space and time scale, i.e., the mega infrastructure construction-environment compound system, new connotations of serious uncertainty arise.

First, the peripheral environment of mega infrastructure construction is a complex self-organizing system. During the long span of construction, the environmental behavior is not only dynamic but also causes complex self-organizing and self-adapting phenomena. These phenomena are not commonly constitutive and generative; rather, they are emergent (see Sect. 5.2.5). Hence, they are a type of uncertain phenomenon with complicated mechanisms. Furthermore, after construction, the new mega infrastructure construction-environment compound system would probably lead to new complex phenomena that have never emerged before in the area. These types of phenomena are difficult to discover and predict based on traditional experiences, knowledge, or conventional methods. That is, based on the large-scale evolution of mega infrastructure construction, its dynamic changes are highly uncertain, and thus, such phenomena have an enormous influence on project approval, argumentation, and decision-making with respect to mega infrastructure construction.

For example, these types of phenomena exist in the sea-crossing project of China's Bohai Sea. According to its design, this project connects Shandong Province with Liaoning Province via an undersea tunnel that is more than 100,000 m in length and is composed of trains that transport cars. The geological conditions in the engineering region are quite complex. For instance, the seabed consists of a rugged landscape with ditches and ridges. Throughout history, there have been many violent earthquakes in the seabed of the Bohai Sea because of the fault along its coastal zone. During the construction and after its completion, when the high-speed rails inside the tunnel have been traveled continuously for an ultra-long period of time, a sequence of new physical factors will be stimulated that may impact the geological conditions over an extended period of time. These potential impacts raise numerous questions. For example, will the tunnel experience sedimentation, cracks, or even collapse? Will earthquakes occur as a result of these new physical factors? After construction completion, will the long-time operation of trains have negative effects on the evolution of the Bohai Sea's ecosystem and cause immense damage to the living environment of the wildlife in the Bohai Sea? All of the above contribute to the self-organizing and evolutionary process of the mega infrastructure construction-environment compound system under a large space and time scale and within an extremely complex environment. These also reflect the serious uncertainties about people's lack of adequate information and cognition.

4. *Serious Uncertainty due to the Mega Infrastructure Construction Subject's Lack of Cognitive Ability*

In general, prior to planning the mega infrastructure construction or during the initial stages of the construction, the mega infrastructure construction management and the management subject tend to lack the necessary experience, knowledge, abilities, and information. It must first be understood that any new mega infrastructure construction is by no means identical to an already completed project. Thus, with respect to the subject, there will be new and unfamiliar information, uncertainty regarding new sites and locations, and insufficient knowledge and skills. Although part of the deficiency is temporary and can be corrected, some of the deficiency will exist until the completion of the project. The situation is analogous to a doctor who has tried many ways to treat a patient but is not completely certain about all of the states and causes of the patient's illness until the recovery of the patient.

The above circumstances are strongly correlated with the serious uncertainty of mega infrastructure construction. If the objective uncertainty is not that serious, it is relatively easy for the subject to recognize the uncertainties and the uncertain types, the knowledge and abilities that are lacking, and the methods necessary to increase capacity. In this way, the subject's ability can be enhanced through self-learning, thus moderately decreasing the level of uncertainty.

The present question is whether the objective uncertainty of mega infrastructure construction is serious. Similar to Schoemaker's suppositions regarding human cognition, there are several possible situations, as follows:

1. Knowing what information, knowledge, and abilities have been mastered
2. Knowing what information, knowledge, and abilities have not been mastered
3. Not knowing what information, knowledge, and abilities have not been mastered

From (1) to (2) and (3) above, it is evident that the subject's subjective uncertainty and the degree of that uncertainty have shifted from general to serious. This shift in the degree of uncertainty manifests itself as the subject's subjective uncertainty increases to the point where the degree of uncertainty is regarded as serious.

In conclusion, each area and level of the mega infrastructure construction management activities represents a unique type of uncertain phenomenon, and this type of uncertainty is even more serious than a general sense of uncertainty, as it will naturally bring many new challenges and problems.

The reasons for this serious type of uncertainty include the following:

1. The integration of the uncertainties formed within different domains and at different levels of construction management
2. The scenario uncertainty formed by mega infrastructure construction under a large space and time scale or as a result of the self-organizing evolution and emergence of a mega infrastructure construction-environment compound system
3. The uncertain emergence of the strongly correlated structure of mega construction
4. The uncertainty that was formed due to the insufficient subjective ability and information, such as the subject's unknown or inadequate understanding of the complex mechanism of mega infrastructure construction and the essential uncertainty regarding the objective principles of construction management
5. The integration of two or more of the aforementioned reasons

Even if the complex formation mechanism of serious uncertainty is not yet understood, it is perceived that the traditional relatively simple analysis and the ideas, tools, and methods used to manage the uncertainty no longer fit because the uncertainty is more serious, intense, and profound than traditional uncertainty.

To maintain uniformity, *we refer to this type of traditional and conventional thought and method arising from the mega infrastructure construction management practical activities that are no longer suitable for the more severe uncertainty as deep uncertainty*. This concept is particularly important for the decision-making and risk management aspects of mega infrastructure construction.

5.1.4 Scenario: Environmental Concept

During the overall process of mega infrastructure construction, construction management activities are similar to each relatively independent but coherent story that occurs chronologically. All of the stories involve settings and plots, i.e., scenarios. On many occasions, the decisions and organizational research with respect to mega infrastructure construction management theory imply that the studies of the scenarios and their changes are integrated into the construction environment and the self-adapting behaviors of the management subjects.

The concept of scenario has been applied in many management areas, but the special properties of mega infrastructure construction endow this concept with new features and connotations. The scenario is a key factor in mega infrastructure construction management theory.

1. *Overview of Scenario*

The concept of scenario stems from the plot development of scripts, thus signifying the sequenced and evolved statements of future plots. Research in the scenario field was first conducted by the military. At present, scenarios are applied primarily in the management domains, including strategic management, policy analysis, risk assessment, and decision-making management. Over the past few years, scholars have assigned various descriptive connotations to the term scenario from different angles, such as the following:

1. A scenario is a developmental process that attempts to describe certain time assumptions. Thus, the possible future and the way to realize it are combined in such a way as to constitute a scenario (Kahn and Wiener 1967).
2. A scenario is a set of reasonable and feasible descriptions about the future but with different structures, internal consistencies, and challenges.
3. A scenario is a descriptive statement that focuses on an optional future (Fahey and Randall 1997).

Though the above definitions of the term scenario appear different, the consensus summarizes the basic connotations of scenario as a scientific concept that could provide mega infrastructure construction management theory with inspiration and significance. Mega infrastructure construction involves a type of practical activity, and it has specific rules. Therefore, the connotations, features, descriptive approaches, and effects of the scenario, as introduced in management problems and as related to the activities, all possess individuality and unique characteristics. Accordingly, the scenarios in mega infrastructure construction management possess their own individuality and unique features. However, for the useful values of this concept to be embodied, this individuality and these unique features must be combined with the general connotations of the above scenarios to form the concept of scenario in mega infrastructure construction management theory.

Then, beginning with the basic connotation of scenario, the important implications of the concept of scenario in mega infrastructure construction management theory can be ascertained.

1. On some occasions, a scenario is a phenomenon about the future, but with respect to mega infrastructure construction management activities, a scenario must focus not only on the future but also on the past and the present, that is, simultaneously concentrate on the reconstitution and reproduction of the scenario. This is necessary because the mega infrastructure construction itself is an important scenario that is embedded in the coherent course of the past, the present, and the future.
2. Although the future scenario of mega infrastructure construction on a morphological level is complicated and deeply uncertain, the manager is able to construct, predict, and imagine the future scenario according to his experiences, knowledge, and deducible causal relationships, to some extent. However, we cannot conclude that the future scenario could be designed and appointed completely by the will of people. Furthermore, some unanticipated scenarios that have never occurred and may even be difficult to imagine or predict may arise in the future, and though these unanticipated scenarios may be beyond anything the engineering designers could imagine, they would cause great potential risk to the project.
3. The future scenarios or the problems of mega infrastructure construction include not only the scenario caused by the environmental engineering system but the scenarios from the mega infrastructure construction-environment compound system. Thus, the project subject must realize that sometimes it is just the mega infrastructure construction itself or the people's behaviors and creations that produce scenarios.
4. Mega infrastructure construction has a sufficiently large space for future scenarios. Thus, it is necessary to establish the concept that any type of scenario may occur in the future because the future involves the present and the past but is not entirely involved in them. Accordingly, we should take into consideration various possible future scenarios that may occur and the types of possible effects these scenarios may have on the establishment and management of mega infrastructure construction. Therefore, the manager should take proper precautions with respect to scenario risks rather than focusing only on those that he thinks have greater possibility merely due to his experience, generally called prospect, and those that appear more ideal, generally called vision. He also cannot remove the unwanted scenarios from the possible future scenario space.

Hence, the concept of scenario in mega infrastructure construction management theory cannot be acquired only through simple means, such as setting different parameters or enlarging possible intervals, because people's cognitive abilities are limited and the scenario causal chain of mega infrastructure construction between the present and the future is extensive and composed of complex associations. There are many things that we know, things that we do not know, and things that we do not know we do not know, a situation that indicates that the theoretical research regarding mega infrastructure construction management is in need of new methods to produce, predict, and discover scenarios.

2. *Scenario Cognition of Mega Infrastructure Construction Management*

We have respectively summarized general scenarios and those involved in mega infrastructure construction management. On this basis, our focus is now on the concept of scenario in mega infrastructure construction management theory.

Using decision-making in mega infrastructure construction as an example, the decision-maker always hopes to make decisions that yield a "good" or solid decision plan. How does one determine if the plan is "good," however? Beginning with the feature that the operating span of mega infrastructure construction and the project have a great influence on the environment, the decision plan should not only be appropriate for the future scenario of engineering environment but also be able to effectively confront and manage the possible changes in the future scenario. That is, its effect on the changes must be robust and stable. Therefore, from the perspective of the significance of engineering risk precautions, a decision plan based on scenario robustness is critically important. Accordingly, only considering the scenarios based on the prospect and the vision is not sufficient because we cannot ensure that the scenarios we believe have a high possibility of occurring in the future will do so, nor can we shape the future scenarios based on our subjective preferences. Faced with such deep uncertainty regarding future scenarios, we can only hope that in various possible future situations, including the most severe, the effectiveness and robustness of the decision plan is sufficient to manage such scenarios.

Based on the important background of mega infrastructure construction management activities, we propose the following scenario concept with respect to the mega infrastructure construction management theory:

A scenario is the macro phenomena formed by the mega infrastructure construction-environment compound system on an overall level, the evolution of the phenomena, and the possible ways the phenomena are formed.

Within this concept, it is necessary to emphasize the following specific points:

1. Construction subjects must understand that the formation and evolution of a scenario, regardless of whether it be in the past, the present, or the future, is a continuous process.
2. The formation and the evolution of a scenario are neither entirely designed nor determined by humans. A scenario is the self-organizing result of a compound system that involves people, projects, and the environment. Because of this, it is the complexity of human behaviors that deeply affect the formation and the

evolution of the scenario. That is, a scenario of mega infrastructure construction represents the background and the conditions of mega infrastructure construction management and is thus produced by mega infrastructure construction.

3. As a general rule, a scenario is a common and ordinary phenomenon, but a scenario of mega infrastructure construction is a concept with complex connotations, especially with respect to the universality of the scenario space, the uncertainty of the formation path of the scenario, and the change and evolution of the scenario, as these are not aspects of a general scenario. These unique properties, however, cannot form a class of specialized scenario rules because they are closely related to concepts such as large scale, complexity, and deep uncertainty.
4. The formation process and the complex shape of a scenario dictate that it is necessary to describe and analyze it through multiple methods and means. For example, we can employ a language with logical connections but without causality to narrate and analyze a scenario. We can also use a structured mathematical model with certain fineness, and we can reconstitute and generate techniques that computers can comprehend and manage. More often, however, we resort to the comprehensive integration of various measures, the contents of which will be introduced in Sect. 4.9 as part of the discussion on special methods of mega infrastructure construction management.

To expand the understanding of the concept of mega infrastructure construction management, we present the following example.

Improving the shipping status and the navigation capacity of the Yangtze River is one of the vital functions of the TGP. Therefore, it is necessary to predict the future traffic scenarios of the surrounding areas and projects and design the ground lock capacity. Since the storage of the TGP in 2003, the freight of the Three Gorges ship lock has annually increased by as much as 12.2%. By 2011, it exceeded 100 million tons. Compared with the original engineering design ability, this scenario has been greatly advanced over the course of 19 years.

The disparity between the future scenario of the engineering environment and the original engineering functional design has become increasingly prominent and has created a bottleneck problem that is restricting the development of the water channel of the Yangtze River. In situations where the lock demand increases rapidly and the lockage capacity is weakened, experts propose the establishment of a new channel for the TGP. However, the site selection, technological difficulties, migration issues, and ecological environment protection are rather complicated. It was estimated that the process of completing the channel will take 15–20 years. This example substantiates that regardless of whether the prediction about the future scenario of the engineering environment is precise, the prediction is important for the scientificity of decision-making regarding mega infrastructure construction.

Following the establishment of the TGP, the project and the peripheral environment formed a mega infrastructure construction-environment compound system. The scientific connotation of the concept of scenario with respect to mega infrastructure construction indicates that after several years, this new system may produce new scenarios that have never before appeared, which is exactly what happened. After the storage of the TGP, the downstream water of the Yangtze River was cleaner and contained less sediment. However, because of the drop in the water level of the Yangtze River, the original intake pipes for residents' potable water and for the industrial water were unable to be pumped. Additionally, because the riverbank of the Yangtze River had collapsed, certain unstable situations occurred in originally stable places, a factor that may cause further potential disasters. Such is the emergence of the new scenarios of the mega infrastructure construction-environment compound system, an event that may greatly influence the actual effects of the functions and goals of mega construction.

The actual situations regarding the two aspects of the TGP in China offer a concrete and vivid reflection on the various scenario phenomena of mega construction and their great value to the studies about the decision-making theory of mega infrastructure construction management as well as the risk precautions.

5.2 The Thematic Concepts in the Theory of Mega Infrastructure Construction Management

In the conceptual system of mega infrastructure construction management, there is a class of thematic concepts that is not as common and fundamental as the general concept. These concepts are more concerned with the abstraction of the characteristics of managerial elements from or with certain management functions of managerial activities in mega infrastructure construction. Generally, the thematic concepts become more involved in the practice of mega infrastructure construction management as the management itself becomes more intense.

5.2.1 The Management Subject and the Core Subject

The management subject of a mega infrastructure construction refers to a group of management subjects who undertake some management task (or function) during some stage of mega infrastructure construction management (Eisenhardt 1989; Ward 1999; Chapman and Ward 2002, 2003). For instance, departments or enterprises, including the government, the construction owner, the construction planner and designer, the contractor, the supervisor, the researcher, and the supplier, are all important members of this group. A group consisting of these subjects has greater ability to manage the complexities of management problems related to mega infrastructure construction, as the members complement each other's functions, experiences, knowledges, and wisdoms. However, since the subjects in the group have different goals and benefit claims, the group must establish a well-formed mechanism for the successful communication and coordination among the subjects. This further requires identifying an individual in the group who is capable of leading and controlling the group. Such a subject may hold a superior administrative position, possess certain resource advantages, etc. Compared with other subjects, the lead subject has broader powers when making decisions and possesses more authority and more discretionary power during the coordination between subjects. *We refer to this subject as the core subject of the management subject group*. Accordingly, the core subject achieves and maintains the integrity and orderliness of the group's activities. In the group, whereas the ordinary management subjects are changeable in accordance with the varying needs of different management functions and tasks, the core subject remains stable throughout the entire management process. The government, including the cosigner, and the construction owner are the common core subjects.

The above concepts are summarized as follows:

1. The management subject of a mega infrastructure construction is generally a group concept. Namely, it refers to a group that consists of many independent subjects. In the group, subjects perform and complete their management tasks under certain institutional rules. As a rule, there is a core subject who functions as the leader of the group.
2. Whether it is the group or the individual subject, the management subject integrates resources, improves competences, adopts or creates solutions according to certain rules, and self-organizes through self-organizing procedure and self-learning behaviors. When problems appear, subjects will compromise with each other, broaden the horizon of recognition, and improve management competence.
3. The core subject updates subjects regarding the construction environment and the management tasks to rectify problems and optimize group competence. In other words, the composition and the structure of the management subject group in the mega infrastructure construction are changeable and flexible.
4. The competence of the management subject of mega infrastructure construction refers to the overall capability of the subject group. It is not the capability of the core subject, nor is it the sum of the capability of the individual subjects by simple addition. In fact, it is the systematic competence that emerges from the group when led by the core subject and constrained by the system rules.

For example, in mega infrastructure construction, there are always problems related to key technology, especially with respect to technology breakthroughs and the obvious threshold crossings, including those in theory, material, equipment, and technology (Harty et al. 2007; Bosch et al. 2011; Xia and Chan 2012; Lessard et al. 2013; Hu et al. 2014). Without breakthroughs and threshold crossing, it is impossible for the subject to solve problems related to key technology. However, for these problems, not only does the local contractor lack reliable experience, but there also exist few precedents in the foreign construction industry. Therefore, the management subject must make breakthroughs in key technology by way of innovation. Otherwise, mega infrastructure construction will lack the corresponding technical support and assistance.

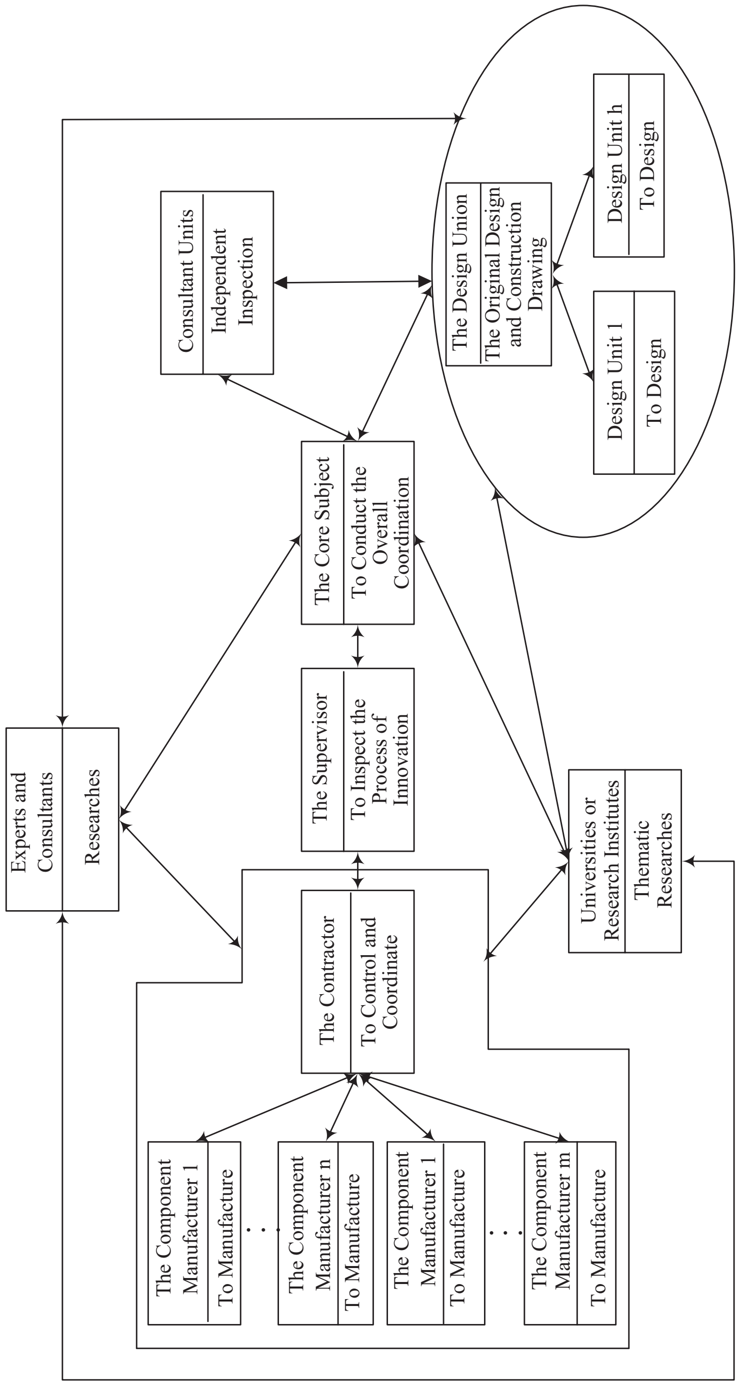

Fig. 5.1 The relationships among the innovation subjects of engineering technology

Obviously, as it is too unwieldy for an individual subject, such as the contractor, to make the technology breakthrough, this problem should be solved with the endeavor of a group of subjects, including the construction owner, designer, construction enterprise, supervisors, research institutes, universities, etc. In this group, the construction owner usually undertakes the task of guiding and coordinating the other subjects, the construction enterprise serves as the main force, and the others provide support. Though each individual subject has his own important functions within the group, due to the owner's core position and his role of leading and coordinating, the owner is more capable than the others to compensate for company shortages in credit or capability, and he also has special advantages in certain fields, such as providing capital, integrating intellectual resources, formulating policies, and arbitrating disputes. Therefore, during the process of achieving breakthroughs in key technology in mega infrastructure construction, the construction owner is the core subject of the group when making decisions about technology innovations.

The figure below depicts the structure of this relationship (Fig. 5.1).

5.2.2 The Management Platform: Concepts About Organization

Platform is a term borrowed from computer science. As such, there is, for example, the software development platform and the software running platform. This term refers to the environment and the conditions (Kogut 1991) by which new systematic functions are to be supported, expanded, and achieved. *The managerial organization of mega infrastructure construction can be understood as a platform in that its essential function is not to provide, whether in a direct or primary way, specific methods and plans for management problems in mega infrastructure construction; instead, it is to provide the environment and conditions within which these methods and plans can be formulated.*

In relatively simple construction management, the post design of the function of the managerial organization, which establishes the function and the corresponding reward-punishment mechanism for each post, is created only to satisfy the needs of the management task. A managerial organization so rigidly designed usually possesses all necessary management competence. However, the management function of mega infrastructure construction is much more complex than this one. For example, during the early stage of mega infrastructure construction, an overall plan, a demonstration, and a design for the construction should be created, and a general schema that contains an analysis of the relationship between the construction and the environment, the construction values and the goals, and the financial mode and the plan for construction work should also be proposed. Moreover, *during the construction stage*, the schema must also include a study of the systematic complexity of the management problems to set goals, integrate resources, establish the managerial organization, optimize the technology path, ensure the on-site execution, etc.

Obviously, these issues are not only extremely complex by themselves but also have sophisticated relationships with each other. Therefore, even a rigid managerial organization is not sufficient to accomplish directly the successful and effective management of mega infrastructure construction. In reality, such effective management can be accomplished only if the designer of the managerial organization, preferably the core subject, completes the following two tasks:

1. Selects the subjects for the group, arranges them in a dynamic way, and exploits the functions of organizing and self-organizing to develop the competences necessary to manage the complexities of the management problems to meet the various demands of project management. This constitutes the environment or system design of the platform for the management of mega infrastructure construction.
2. Establishes working regulations and procedures within the group such that the necessary competences previously identified can be achieved and put into practice. This is the condition or mechanism design for the platform.

A platform such as this gathers experiences, knowledge, and wisdom from experts in different fields in an adaptive way, and it integrates and allocates all types of management resources. In this way, it guarantees the formulation of necessary management competences.

Thus, for the management of mega infrastructure construction, the foremost function of a platform is not to bring forth a specific schema to underscore and solve the complexity of management problems but to create an environment in which and the necessary conditions by which complex managerial problems can be solved and relevant competences can be achieved. The platform, then, constitutes the fundamental management function of the group, most especially of the core subject.

Accordingly, this suggests that the insight regarding the mode of management organization in mega infrastructure construction is essentially the result of designing and selecting a management platform. Currently, because China is undergoing a social and economic transformation, the name for a mode of project management may remain the same, such as the Department of Construction Headquarters, but the management function and the mechanism of the mode may change constantly. Accordingly, this indicates that the basic meaning of the management mode as a platform for project management has changed profoundly. Therefore, when analyzing and comparing management modes of mega infrastructure construction to determine which mode is more appropriate and reasonable, it is not advisable to view the mode literally in a simplistic and conceptualized way but, on the contrary, to consider the competences in creating an environment and establishing the conditions that enable us to control the complexities of the management problems.

For instance, the Sutong Bridge is a highway bridge built at the beginning of the twenty-first century in China. It lies at the estuary of the Yangtze River with a full length of 32.4 km, and the length of the portion crossing the Yangtze River is approximately 8.2 km. The main body of the Sutong Bridge is a steel box girder cable-stay that has seven spans, where the primary span extends to 1088 m. The construction of the bridge began in 2003 and was completed in 2008 at a total investment of 8 billion RMB. The bridge has a life expectancy of 100 years.

The complexity of construction technology and project management regarding the Sutong Bridge is exceptionally prominent because its construction faced huge challenges, such as poor weather conditions, complex hydrological conditions, deep bedrock issues, and high navigation requirements. Upon its completion in 2008, the Sutong Bridge had the largest oblique-stayed bridge span, the deepest group pile foundation, the highest tower, and the longest cables of any bridge in the world. To manage the complexities of the problems in the construction organization and management of the bridge, the construction owner devised and established a mode of organization and a management platform that was led and coordinated by a provincial and ministerial department that was tasked with seeking technology support from experts. In other words, the mode was to establish a coordinated lead team from members of the provincial and ministerial departments to study and solve major issues related to the construction of the bridge; to employ, through the Ministry of Transportation and the government of Jiangsu Province, experts from all over the world to establish a technical consulting team and an expert technical team; and to invite the world-renowned company COWI from Denmark to provide technical support. The practice proved that the platform plays an important role in every stage of the construction and that it achieves satisfactory results. More specifics are detailed as follows:

1. Provincial and Ministerial Level Lead and Coordinating Departments

The lead and coordinating team of the provincial and ministerial levels of the Department for the Sutong Yangtze River Highway Bridge was founded by the Ministry of Transportation and the government of Jiangsu Province to assist in the construction of the Sutong Bridge. This team, as the highest decision-making body, retains leadership throughout the construction period. It makes decisions and coordinates the major issues through the regular and irregular joint meetings of the ministerial and provincial departments.

During the construction, the lead and coordinating team for the Sutong Yangtze River Highway Bridge provided the Ministry of Transportation of China and the government of Jiangsu Province with top leadership and with the authority to implement macro management, which created amiable support for the construction work and helped to maintain a positive environment for the operations related to technology, work, investments, resources, and policies.

2. Expert Technical Support

The Sutong Bridge is one of the most complex bridge constructions in today's world. More than 100 experiments and technology studies concerned with the key technology have been conducted for the construction of the Sutong Bridge, and many world-class technology problems have been overcome.

With the assistance of intellectual powers, both domestic and abroad, the construction of the bridge resulted in independent technology innovations. The integration of these intellectual powers resulted in breakthroughs in key technologies and facilitated the tackling of challenging issues. Accordingly, the construction team invited world famous bridge experts as technology consultants and established expert teams to provide suggestions regarding technology. This is the first time that China invited COWI to participate in a construction project and to provide whole course consulting services on technology and construction management. The technology consultants, expert teams, and COWI became the three major technology supporters for the construction of the Sutong Bridge.

Considering two aspects, the necessary administrative public power and the engineer technology, the platform was built to create the environment and conditions necessary to determine the complexity of the management problems and guarantee the development of corresponding competence.

5.2.3 Multi-Scales: Behavioral Concepts

In managerial activities of mega infrastructure construction, distinguishable levels or orders within the same scale can be found in the characteristics, elements, and parameters of the management. This phenomenon is called the multi-scale of mega infrastructure construction management. *The multi-scale of mega infrastructure construction management is a concept that extracts the orderliness and stratification presented on the same scale by a managerial characteristic or a management element in managerial activities of mega infrastructure construction*. However, determining whether the character or the element is qualitatively or quantitatively described is not important.

The multi-scale of mega infrastructure construction management is a real property of managerial activity and management problems. Introducing this concept and applying it to the theoretical research of mega infrastructure construction management have a significant effect on the precise analysis of the complex structure of management problems of mega infrastructure construction and on the solutions that are subsequently devised.

Thus, at this point it is necessary to describe several management elements or phenomena that are multi-scale in the managerial activities of mega infrastructure construction.

1. *Multi-scales of Time*

Modern mega infrastructure construction is often expected to survive for at least 100 years. If this span of time is to be regarded as a large time scale for construction, then the years spent designing the construction and completing the site works can be viewed as a small time scale, and the time spent constructing the project, which lies between the large and the small time scales, should be considered as the middle time scale. Though it is not a strict distinction, it is absolutely clear and important for mega infrastructure construction management. Activities, phenomena, and problems in mega infrastructure construction management have various properties and characteristics based on the various time scales, and as a result, it requires us to distinguish among those scales and resolve problems based on the different management ideas and methods aligned with the corresponding time scales. For example, within the small time scale, the crucial task of mega infrastructure construction management is to construct a complete project entity. Therefore, it is important during this period to design and realize the physical functions of the project entity, which includes the integrity and quality of the physical function. However, within the large time scale, the core task is to maintain the physical functions of the construction, which includes inspecting the health of the construction and ensuring its stability and nonstop operation.

2. *Multi-scales of Space*

The multi-scale of space is derived from the property of mega infrastructure construction in two aspects.

First, mega infrastructure construction, which is characterized by its enormous size, is obviously an entity with a large space scale. For example, the Qinghai-Tibet Railway, which extends for 1956 km, crosses vast regions of high altitude in western China. The South-to-North Water Transfer Project, a national strategic project that aims to lessen the stress of water shortage in northern and northwestern China, is divided into three lines, namely, the east, middle, and west, that connect the Yangtze, Yellow, Huaihe, and Haihe Rivers, among which the eastern route, which covers five provinces, and the middle route, which spans four provinces, supply water for more than twenty cities. The West-to-East Gas Pipeline Project, which delivers natural gas in western China to eastern China via two parallel caliber pipelines with radii of 1.5 m, begins in the western Tarim oil and gas field in Xinjiang Province and ends to the east of the city of Shanghai, thus traveling across seven provinces and extending for 4200 km. It is evident that these constructions, which span such immense geographical space, will inevitably confront regions and natural environments that have different space scales, and as a consequence, these differences will be revealed, and management problems will arise as a result of the huge diversities.

Second, the range of the impact and the radius of the effect of mega infrastructure construction occupy a large space scale. With respect to mega infrastructure construction, whether it is direct, indirect, or emergent, whether it is positive or negative, and whether it is presented explicitly or implicitly, the impact or the effect of the construction always affects vast areas, even if the effect is related only to some direct physical functions of the construction that seem, on the surface, to affect only a small space within the construction. These physical functions will gradually cast their impact or effect on the social economy and ecological environment and extend over a larger spatial area. Based on this setting, it is evident that functions of mega infrastructure construction can be divided, according to the multi-scales of space, into three levels, a large space scale, a middle space scale, and a small space scale.

For instance, the generation of hydroelectricity of the Three Gorges Project is related directly to a small scale space that includes the dam, the reservoir area, etc. However, the discharging of a huge amount of clean water from the reservoir, which causes the collapse of the bank in the downstream and deepens the outlet of Dongting

Lake, which then leads to a dramatic decline in the water reservation of Dongting Lake, indicates the derivative function of the project in a middle scale space. When it arrives at the estuary of the Yangtze River, the discharged clean water cuts off the continuous supply of sands, which terminates the previous plan of the Shanghai to reclaim land in the estuary. This is an indication of the project's function in a large scale space.

Moreover, the space multi-scale is found not only in functions of mega infrastructure construction, where the construction work is industrialized, but also in the bulk source supply chain related to the work site of mega infrastructure construction. For example, the steel box girders required by the Hong Kong-Zhuhai-Macao Bridge, which weigh more than 40,000 tons in total, were produced by factories located in the northeast, east, central, and other areas of China, which are over 1000 km from each other. This supply network is distributed over a multi-scale space, which, on the one hand, ensures the amount and quality of the supply of steel box girders for the construction site and, on the other hand, brings new complexity to the construction logistics coordination and management.

The multi-scales of mega infrastructure construction management are not just found in the quantifiable physical elements, such as time and space, however. In fact, any management elements could be said to have multi-scales if it demonstrates orders and levels at some scale. Therefore, the concept of multi-scale can be applied to any management element, even if the element can be described only through a qualitative method. The following cases belong to this type.

3. *Multi-scales of Hierarchy*

The project demonstration of mega infrastructure construction in the early stages requires a systematic exploration of topics, such as the social and economic benefits of the project as well as the project's technology applicability. For instance, a serious investigation into tens of relevant issues regarding the project demonstration of the Hong Kong-Zhuhai-Macao Bridge was conducted. These issues were classified into a hierarchical structure of three scales, namely, the macro, intermediate, and micro scales, upon which a comprehensive decision-making system was established. In addition, there is also a type of multi-scale concept regarding the importance of management targets. For a complex management problem with multiple targets, these targets can be ordered according to an analysis of their importance, and a rule that the subsequent target should follow from the preceding target can then be established. Because of the "one country, two systems" policy, the construction of the Hong Kong-Zhuhai-Macao Bridge required the determination of which mode of cross-border passing ports should be adopted. According to the rule of target importance, the weights should be allocated into scales, such as jurisdiction, society, economy, management, and technology, and the location of the ports must align with the jurisdiction. To conform to the "one country, two systems" policy, the jurisdiction must have more weight than the other scales. Therefore, the complexity of this decision-making problem is greatly degraded by the concept of the scale of importance.

4. *Multi-scale of Complexity*

The system complexity is an essential property of mega infrastructure construction management, and it is the starting point for studying it. Furthermore, if considered from the perception of cognition, it is a holistic concept. However, regarding particular managerial activities of mega infrastructure construction, it is inappropriate to adhere to the philosophy that complexity is a monolithic whole given that it varies with degrees. For example, complexity can be divided, according to its severity or intensity, into three scales, namely, minor, moderate, and major scales of severity or intensity. Generally speaking, complexity of a minor scale relates to common system issues, including the issue of specialized functions such as quality control and procedural management in mega infrastructure construction; complexity of a moderate scale is equivalent to the complexity of problems such as the generative function of the construction and coordination at the construction site; and complexity of a major scale includes issues related to the analysis of emergent functions, the work of project demonstrations, and the discovery of and prediction of the construction scenario.

5. *Multi-scale of Agency Relationships*

As a public product, mega infrastructure construction has a multi-level government principal-agent relationship that is led by the government, and it has relationships with the public; government agencies; government departments; professional institutions; project owners, i.e., core subject; and project managers. These relationships represent the essence of the organizational mode of mega infrastructure construction and are extensions of the subject and core subject concepts in the theoretical system of mega infrastructure construction management. Thus, they all contribute to the development of the principle of the hierarchical principal-agent relationship, which plays a significant role in the organizational mode of mega infrastructure construction management (see Sect. 6.5).

In this relationship, the government is committed to the public to control the construction work as well as the management work of a mega infrastructure construction. In this sense, the government becomes the public agent with the widest agency relationship, thus determining that the government will adopt the values that transcend the benefit claims of ordinary management subjects. The government department represents some function of government and is also committed to the public. However, unlike the government, the government department has a narrower agency relationship than its peer or superior units because it undertakes only part of the function of the government. Due to their value orientations and benefit claims, the rest of the members in this relationship, such as the professional institution, project owner, contractor, supplier, and supervisor, usually have a working unit or an enterprise as its clients. Accordingly, the agency relationship in mega infrastructure construction management is a multi-scale structure in terms of the width of the relationship such that the government is at the top and the others are situate below the government.

6. *Multi-scale of the Structure of Problems*

To study the management problems of mega infrastructure construction, we must first describe them. Comparatively speaking, among various management problems, there is a type of problem that can be described in terms of its structure, the logical relations among the elements of which the problem is composed and the input-output relation depicted by strict inferences and processes. This type of problem is called a structural problem. Generally speaking, technology problems and problems related to natural laws belong to this type. If the management problems have some part that cannot be described clearly in terms of the structure or the logical relation or they have ambiguities in the representation of the relationship, then the problem belongs to a type of problem called a semi-structural problem. For instance, in mega infrastructure construction, if some management problems are concerned with the social-economic effect of the construction, then they always fall under the category of semi-structural problems. The last type of management problems is the non-structural problem, whose description is the least clear and accurate. These are problems that focus on people's behaviors, mental actions, and values.

It is evident that it is easier to describe, analyze, and solve the problems with a clear structure and more difficult to do so for those problems that are less clear and those whose methods and technologies, when applied to different types of problems, differ as well. Therefore, we propose the multi-scale concept to classify the structure of problems.

Apart from the multi-scale concepts previously mentioned, we can also find the phenomenon of multi-scales in fields such as the flexibility of a management organization, the iteration mode of forming a management schema, and the diversification of the management subjects.

In conclusion, the phenomenon of multi-scales is common in the management of mega infrastructure construction. The core idea of multi-scales is that, in mega construction management problems, the characteristics of management elements on the same scale vary in degrees and order. A change in the degree or order indicates that the same element will have different properties and characteristics, which requires us to study these properties and characteristics, as well as their consequences, in managing a mega infrastructure construction and when conducting relevant research. Thus, it has been determined that the concept of multi-scales is a useful tool for managing the complexity of management problems in mega infrastructure construction, and it helps us to develop the working regulations with respect to management work.

5.2.4 Adaptability: Behavioral Concepts

5.2.4.1 Two Basic Types of Adaptiveness

Mega infrastructure construction management is often conducted in situations where there exist great uncertainties and where management problems are always composed of various complexities (Gallagher 1995; Williams et al. 1995a, b;

Flyvbjerg et al. 2003). Hence, management subjects must possess the competences to be able to know/recognize, analyze, and manage these complexities because, without such competences, subjects would not understand the complexity of the problems with which they are confronted and would be unable to manage the complexity.

However, every individual management subject possesses limited intelligence and is subject to deviations in recognition and values (Smith and Winter 2005), which implies that it is impossible, in general cases, for any single management subject to possess the comprehensive competences. In fact, it is even difficult for a group of management subjects in mega infrastructure construction to possess the full range of competences necessary to manage and resolve the complexities with absolute certainty. Accordingly, this situation is common in mega infrastructure construction management and gives rise to an important question. How does the management subject develop the competences necessary to manage such the complexities, and what constitutes the development process?

John Holland's famous assertion that "Adaptability builds complexity" (1995) provides a perfect annotation to this question, and it seems plausible that this assertion can, to a large extent, be regarded as the answer to the question.

The term adaptation is derived from the Latin word adaptatus, whose original meaning was to adjust or alter. Though this term may have different meanings in different disciplines, the basic meaning remains. That is, "subjects change positively their features, behaviors, organization modes or functions to adjust to the environment and conditions, so that they get accustomed to the new circumstance and keep surviving, developing and functioning." The behavioral competence for adaptation is called adaptability.

According to the concept of adaptation, it is easy to understand that mega infrastructure construction management subjects improve their behavioral competences of knowing/recognizing, analyzing, and managing complexities through the process of adaptation. Subjects' adaptive behaviors assume different forms because of the differences in managerial activities as well as the autonomous behaviors of the subjects.

Moreover, in addition to the subject's behaviors, the management program, which is the major product of the subjects' behaviors, also experiences a type of adaptation, namely, the adaptation of the management program to a situation that is profoundly altered. The adaptations of the subject and the adaptation of the management program are two of the most basic and fundamental types in the category of adaptability.

1. Type 1: Subject Adaptability

In managerial activities of mega infrastructure construction, subject adaptability refers to how the subject interacts with various elements to achieve and reinforce the competence necessary to solve the complexity of management problems through the accumulation of continuous learning and experiences. For example, a subject's understanding of the essence of a management problem involves a process of learning that proceeds from knowing only one part to knowing the whole and from knowing superficially to knowing profoundly. Through this process, the subject is able to strengthen his understanding of the complexity of the management problem. Furthermore, the subject adjusts, properly and timely, his management ideas, targets, organization structure, and mode of behaviors to meet the requirements of the management work, through which the subject's competence to know/recognize, analyze, and explain the management problem is reinforced. This adaptability is derived primarily from the subject's autonomy and self-organizing, which is a form of active adaptation.

The subject's adaptability plays a key role in improving his competences. In fact, the subject's competences are neither static nor unchangeable. The competences that actually work in project management emerge from continuous adaptive learning and experience accumulation under the effect of theoretical thinking with respect to project management and engineering thinking. This is because new competences are achieved by changes in the subject's behavior mode and organizational structure, which may include the reconstructing of the subject's organization. More succinctly, the fortification of the subject's competences is not only the goal but also the result of the subject's self-adaptive behaviors.

A summary:

1. *Adaptability is a basic behavioral principle to which the management subject conforms in managerial activities of mega infrastructure construction to manage the great uncertainties in the environment and the complexities of management problems.*
2. The strength of the subject's adaptability is an important standard for measuring the subject's management skills and qualities.
3. The adaptation competences are the result of subject's self-learning and self-organizing. In this sense, it is the subject's live and active response, including pre-response, when confronting complex management problems, and it is also a phenomenon of the systemic managerial activities derived from the mutual interactions between the complexity of the problem and the subject's adaptation.

2. Type 2: The Adaptability of the Management Program

It is evident that the final purpose of the successful management of a mega infrastructure construction is not to improve the subject's ability to adapt but to use the subject's enhanced ability to create a management program characterized by high standards and high quality to ensure that complex management problems can be resolved effectively. The adaptability of a program is the product of the subject's adaptability, which, by itself, is a special type of adaptability. Thus, we must stress this phenomenon, namely, that the adaptability of the program occurs when the situation has been profoundly changed.

Due to its long life cycle, mega infrastructure construction requires a management program, especially a decision-making program, to ensure validity throughout the life cycle of the program. This implies that the management program indicates not only the physical quality of the construction entity but also whether the construction functions well when changes or situations with great uncertainties emerge. In other words, the program should ensure that the construction will not be negatively impacted by unexpected conditions. Otherwise, the construction could be damaged and even lose its ability to function. This characteristic of the management program reveals another scientific meaning of adaptability with respect to the management program.

According to system theory, every management program of mega infrastructure constructions is a complex artificial system designed by the subject. The effectiveness of the program is another form of the overall function of the system. However, there is a range of environmental variance within which a function's behaviors are considered normal. If the range is wide, the program is considered to be more competent in resisting severe external interruption, and thus, it is said to not be sensitive to environmental changes. From the perspective of the management program, the competence of anti-interruption declines over time. This means that the competence of adaptability also weakens with time, which is similar to the change in the human body such that the body tends to be more unaccustomed to changes in the external environment and less resistant to disease as it ages. The environment of mega infrastructure construction changes constantly, and the change is not limited to a narrow range, as was expected. Therefore, whether the construction has a strong competence to adapt to environmental changes is an important property of the quality of the management program and an important index for assessing the subject's final achievement.

It is further evident that the adaptability of a program is not identical to the adaptability of the subject, which indicates that the adaptability is not the result of the active response of the subject to environment change but rather represents the product of the subject's response to environmental change. In other words, it reflects the quality of the function of a complex artificial system. Essentially, the adaptability of the program is a measurement of the coupling degree between the program's effect and the profound change in the construction environment on a large time scale.

Therefore, a set of methods to measure the adaptation must be constructed. For example, the technology that enables the prediction and discovery of the environmental situation, as well as its change, in mega infrastructure construction must first be studied, as must the method used to measure the exchange between the program function and the situation change. It is apparent that the technology and the method are quite different from those used to make normal predictions and measurements in common construction management scenarios, as the problems confronted in mega infrastructure construction management have their roots in the great uncertainties of the overall behaviors of a complex system that cannot be resolved without methodology innovation. Due to its length, this topic is discussed in Chap. 6, "Principles of Scenario Robustness," and in Chap. 7, "Decisions under Great Uncertainties in Mega Infrastructure Construction."

If we combine the two adaptabilities, a logical chain based on the idea of adaptability is created: adaptability of the management subject → improvement in adaptability → the result of adaptability, i.e., the management program → the adaptability of the management program.

The subject's adaptability has many manifestations in management work, such as the adaptability of management organization, the adaptability of the formation path of the management program, and the adaptability of management goals. It is argued herein that with respect to the management work of mega infrastructure construction, the adaptability of the management subject is of fundamental importance and plays a dominant role, while the adaptability of the management program is a reflection of the quality of the subject's adaptability and, as such, provides a particular criterion that most sufficiently represents the quality of mega infrastructure construction. Therefore, the two adaptabilities are adopted as the basic content of the concept of adaptability, and other types of adaptability are regarded as extensions and derivations of these two adaptabilities. In this way, the basic concepts of the theory of mega infrastructure construction management can be more concise.

5.2.4.2 The Significance of Subject Adaptation

As previously noted, the adaptability of the management subject is achieved through continuous learning and experience accumulation as a result of the subject's interactions with the environment and with other management subjects. Thus, self-learning provides an important premise and a main path for the adaptability of managerial activities of mega infrastructure construction. Since the management subject in mega infrastructure construction is usually a group of subjects, the subject's self-learning activities should be understood as the group's activities. A major sign of these activities is the group's consensus regarding complex management problems.

To solve the complexity of management problems in mega infrastructure construction, knowledge from different backgrounds and the consensus of the subject group are essential. In the beginning, each subject in the group has only his own experiences and knowledge, both of which differ from those of the other subjects in the group in terms of perspective, level, and field. It is from this that each subject builds his own understandings regarding the complexity of management problems. Therefore, the understanding of each subject differs from that of the other subjects in the group. This non-consensual phenomenon appears in the early stage of the process of the subject's understanding. During this stage, the understanding of each subject may contain correct opinions and true wisdom as well as prejudices and fallacies. Hence, the subject must gather opinions that are true and correct and revise and improve opinions that are fallacious. Thus, the self-learning of the subject group is the process of continuously revising, supplementing, and completing the non-consensual understandings in an effort to establish more scientific and accurate understanding of the concept to eventually achieve consensus. Undoubtedly, the consensus finally reached is more scientific, comprehensive, and profound than were the non-consensual understandings. Thus, the reaching of consensus is the optimization of the subject's self-learning.

1. The Basic Rule of Forming Consensus in the Subject Group

The process of reaching consensus regarding the complexity of management problems includes the subject's treatment of the data and information and the transformation, conversion, and mining of the data and information. During this process, the subject must analyze the data, but more importantly, the subject must synthesize the competences of imagery thinking, abstract thinking, and creative thinking. For example, whereas the knowledge that people have is usually simple and certain, their knowledge regarding complexities and great uncertainties is not as accessible to them. Therefore, people must integrate the simple and certain knowledge to manage problems that are more complex and uncertain (Munns 1995; Meyerson et al. 1996; Dixon 2000; Cook 2001; Heimer 2001). This involves the process of trial and error in terms of epistemology, wherein the knowledge and wisdom of people play a crucial role. Again, it is noted that the subject mentioned herein is not an individual subject but a group of subjects. This is because the group of individuals is more likely to have knowledge and wisdom that is more comprehensive and accurate than the individual, and it is the group that is more likely to develop the overall capacity to work with the complexity of problems.

In the field of epistemology, consensus is understood as the essential property and general rule of management problems as grasped by the subject group, and thus, the formation of consensus emerges from the cognitive behaviors and competences of the subject group. Therefore, consensus represents the advantage of the group over the individual regarding the competence of knowing. The consensus is not the mechanical addition of an individual's knowledge, nor is it subject to the rule of the minority being subordinate to the majority. In the process of knowing, complex management problems evolve from the non-consensual stage to the consensual stage. Thus, there is always the need to compare, filter, and revise opinions of individual subjects. Accordingly, after several runs in which these opinions are collected and analyzed, there is finally a convergence resulting in consensus. This entire process is not only the result of the new entire cognitive process of collection but also the result of the adaptability of the group.

2. The Basic Path of Forming Consensus

According to engineering thinking, the path for a group to reach consensus on a concrete issue in a mega infrastructure construction is considered special and unique. However, when beginning from the basic principle of forming consensus, we find that the group of subjects has its own path to form consensus, a path that consists of the following four stages:

1. Integration

In this stage, the main task is to select, according to the characteristics of the problem and the requirements for the solutions, the individual subjects and then to choose a core subject to design the rules for the operation of the management platform. For instance, when attempting to solve the problem of a key technology program in mega infrastructure construction, the project owner will hire experts and consulting units, whether domestic or abroad, from different fields and of different levels. These subjects will participate in studies with designers and contractors. When selecting subjects, special attention should be given to the diversity of the subjects to include vertical and horizontal differences. The vertical difference is concerned with subjects, while the horizontal difference is concerned with subjects' backgrounds and expertise. Moderate diversity among the subjects will guarantee breadth and comprehensiveness of the subjects' suggestions. For some complex problems, the time to reach consensus will be much longer if the diversity is too great. Thus, it is reasonable and necessary to strive toward moderate diversity.

2. Interaction

The experts may have different, even conflicting, opinions regarding complex problems. When this occurs, subjects must modify and adjust their opinions through the process of discussion and argumentation. Because every expert tends to draw from his own experiences and competences, it is difficult for them to reject or discard their opinions. In such situations, the core subject, who serves as the organizer and leader of the group, must lead the discussion, coordinate the various opinions, summarize the results of the discussions, and, ultimately, lead the group to consensus.

3. Check

The consensus reached via the collection of opinions must be scientifically verified. This verification is the testimony for the consensus of the group with respect to the applicability of the construction as well as the on-site operability, it is the testimony of the engineer's ideas with respect to engineering technology and engineering principles regarding the construction site, and it is the process of combining engineering thinking with theoretical thinking. Though some theories regarding consensus are correct, it is possible that the consensus can be revised when difficult problems arise at the construction site. This clearly reveals the importance of engineering thinking.

Generally, the check for the group's consensus must cover its applicability in the fields of technology, finance, and the environment.

4. Consensus

Though the process of forming consensus often produces new knowledge, when applying new knowledge to management, we must adhere to the principles of engineering thinking, be flexible, and never set permanent restrictions on it. Moreover, it is critical to note that consensus is not rigid, and thus, we must always be prepared to update and revise such consensus according to its actual effect in the construction site.

The four stages are diagramed in Fig. 5.2.

5.2.5 *The Function Spectrum: Concepts Regarding Goals*

What function of a mega infrastructure construction most clearly indicates the purpose and intention of the construction?

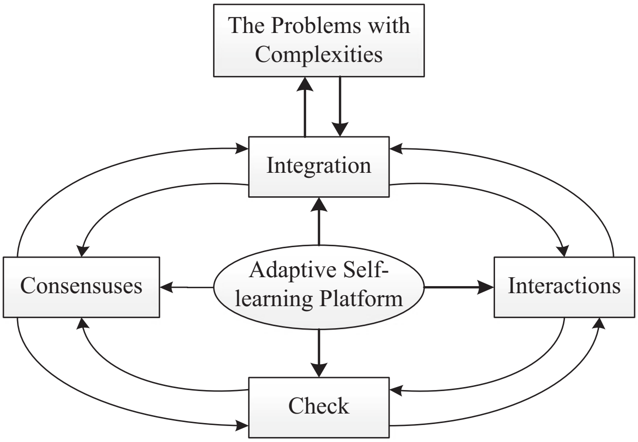

Fig. 5.2 The basic process of forming consensus in the subject group

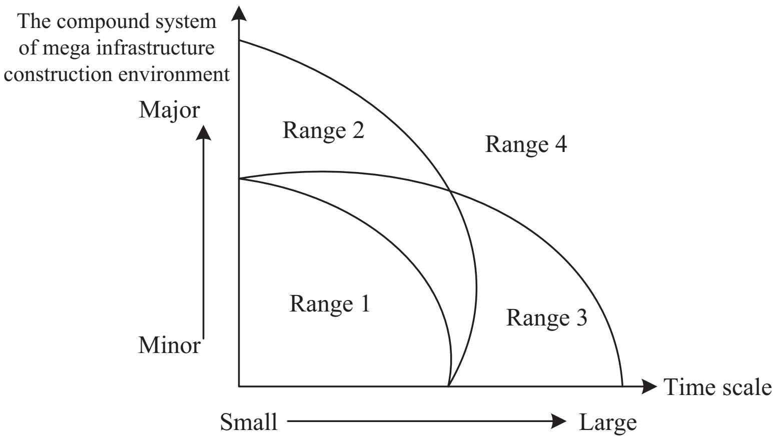

Fig. 5.3 The constitution diagram of the function spectrum of mega infrastructure construction

In practice, because of its long life cycle, mega infrastructure construction is characterized by a large time scale. Additionally, this factor contributes to the high complexity of the compound system of mega infrastructure construction environment. Thus, we can investigate the function spectrum of mega infrastructure construction by applying our analyses of the time scale and the complexity of the compound system of a mega infrastructure construction environment (see Fig. 5.3).

In Fig. 5.3, the various functions of mega infrastructure construction can be classified into three ranges. Range 1 refers to those functions that require a small time scale and exhibit minor complexity in the compound system of the mega infrastructure construction environment. In this range, the construction environment is stable overall, and the impact of environmental change and resulting interruptions on the effectiveness of the construction is relatively minor. Functions of mega infrastructure construction in this stage, which include the most basic and direct physical functions, are derived from the construction's hardware. Thus, the functions in this range are called *constructive functions*. For instance, the function of the bridge is to connect traffic, the function of the canal is to improve navigation, and the function of the hydroelectric dam is to generate electricity. All of these functions belong to the category of constructive function.

Range 2 refers to those functions that have a small time scale but are of moderate complexity in the compound system of the mega infrastructure construction environment. In this range, the construction environment changes slightly over time and has a small impact on the effectiveness of mega infrastructure construction. However, with the construction being completed, new situations in the new compound system of the mega infrastructure construction environment may appear, which may further trigger scenarios that are detrimental to human society. These detrimental functions do not evolve directly from the physical functions of mega infrastructure construction but from the interactions between the physical structure of the construction and the new situations in the compound system. All of these possible functions are within the category of *generative functions*, and though they do not belong to the constructive function, they are the results of the radiation, derivation, and extension of the constructive function. For instance, when a mega transportation construction is completed, it will attract populations and promote the development of estate industry as well as tourism. Thus, generally speaking, Range 2 is composed of both the constructive function and the generative function.

The functions in Range 3 are characterized by a large time scale and moderate complexity in the compound system of the mega infrastructure construction environment. In Range 3, the environment may change and evolve violently for a substantial period of time following the completion of the construction. In such a situation, it is possible for the change and evolution to have a significant impact on and interrupt the function of the initially designed construction, which may generate derivative and extensive functions in the compound system of the mega infrastructure construction environment. For instance, after the construction is completed, variation in and transformation to the regional culture gradually occur due to cultural accumulation over the long term. Thus, Range 3 exhibits both constructive and generative functions.

Range 4 refers to functions that are characterized by a large time scale and the highest degree of complexity in the compound system of the mega infrastructure construction environment. In addition to the independent influence of the large time scale and the high degree of complexity, time also interacts with the system, which gives rise to more situations with higher degrees of complexity at different levels in the system. For instance, the influence of mega infrastructure construction and the function of the compound system of the mega infrastructure construction environment spread gradually from a part of the environment to the whole of the environment. Thus, the transition relation in the function chain is much longer, and the function itself may take effect in levels, which may obscure the causal relation between the two sides of the function chain. In this stage, the new compound system may generate new effects that feature suddenness, uniqueness, and imperceptibility, characteristics that are not as predictable and explanatory as the constructive and generative functions. Because they appear emergently and implicitly, these functions are called *emergent functions*. For instance, the large-scale water conservancy and hydropower engineering construction will reduce the speed of water upstream, thus allowing the breeding of microorganisms and parasites, which then causes the spread of infectious diseases and damages the living environment of humans. If this occurs, it will result in a mass immigration, and the original inhabitants will be deserted. In addition, the dam alters the regional climate, especially the rainfall in the downstream area. Because of the water conservancy due to the dam, the lakes downstream, which once were abundant with water, gradually dry up, which, in turn, speeds up the process of people abandoning the downstream area and immigrating to other places. Thus, in Range 4, there are constructive functions, generative functions, and emergent functions.

According to the preceding discussion, it is evident that the construction decision-makers have made considerate attempts to design and build better constructions to maximize the benefits and that, due to the complexity of man-made systems, it is impossible to avoid the appearance and emergence of other types of effects or functions when a construction is completed. These effects or functions may be either positive or negative because, when people develop and complete a construction with intended explicit results, they also sow the seeds of implicit effects and do not know what the seeds will bear. In the management of mega infrastructure construction, it is important to pay attention to and consider the unexpected effects as well as the possibilities of generating emergent harmful results from these effects. Once the harmful results occur, the original goals of the construction may be sufficiently impaired and may give rise to significant deviations and errors during the process of decision-making in mega infrastructure construction.

Based on the formation of the functions of mega infrastructure construction, the functions of mega infrastructure construction reveal an overall tendency that extends from the generative function to the emergent function according to the change in time and the complexity of the compound system of the mega infrastructure construction environment (see Fig. 5.4). *The range of functions is called the function spectrum of mega infrastructure construction.*

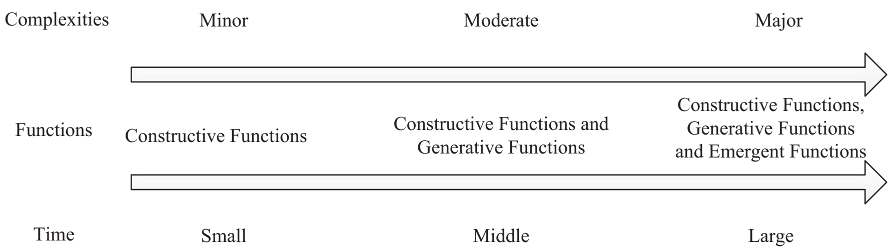

Fig. 5.4 The function spectrum of mega infrastructure construction

The function spectrum is an important attribute of the function of mega infrastructure construction, as it demonstrates the complex diversity of the structure of the functions and includes the structural constitutive function, semi-structural generative function, and non-structural emergent function.

Originally, the design of the mega infrastructure construction reflected the engineer's purpose for building the construction. Therefore, the function spectrum is a concept related closely to the engineer's target (purpose) as well. In more common cases, where the construction evolves from a general project to a mega infrastructure construction, the target also evolves from a single target or multiple targets to a target system, and the dimension or the level of targets increases as well. Thus, the concept of function spectrum not only enriches the meaning of the project target in terms of dimensions and levels but also expands and couples the project target within the same dimension. More succinctly, the targets of mega infrastructure construction differ not only in their levels and dimensions but also in the degree of the spectrum. The function spectrum indicates that even if the intent when designing a mega infrastructure construction is good, the generated and emergent effects may be counterproductive to this purpose. This not only enriches our knowledge regarding the functions of mega infrastructure construction but also reminds us that designing a mega infrastructure construction bears more risk than designing general projects. Accordingly, the function spectrum of mega infrastructure construction can also be understood as the target spectrum of mega infrastructure construction.

5.3 The Logicalization and Systematization of the Concept System

Nine basic concepts are proposed in an attempt to establish the concept of mega infrastructure construction management theory. This concept is, at first, the refining and abstraction of each important link in the management practical activities and the essential attributes of the significant components. As such, it is the basic unit of people's cognition toward management activities. The basic concepts proposed to establish the mega infrastructure construction management theory should fundamentally demonstrate the identity, universality, and regularity of the management activities and the attributes of the management problems, rather than proposing an illustrative concept by which to study a concrete issue in the way done in a mature theory system. Such an illustrative concept often lacks the significance and effects of a theoretical extension.

Thus, whether the nine basic concepts meet the above requirements and form logical and systematic correlations will determine whether the mega infrastructure construction management theory we plan to build has a reliable and solid foundation.

To this purpose, we first review the statement regarding the thinking principle of the mega infrastructure construction management theory. That is, regardless of the types of questions raised in the study of the mega infrastructure construction theory, the essential attributes of these questions are treated as exhibiting systematic complexity. Although this statement is concise, as a principle, it examines the quality and the significance of the basic concepts addressed herein.

When these basic concepts are introduced, the backgrounds of their actual management activities, including the phenomena, scenarios, and subject behaviors, are all specifically explained and described. Thus, it is evident that the nine basic concepts are all derived from the actual activities and phenomena of mega infrastructure construction, and thus, they share the same attributes of the systematic complexity of mega infrastructure construction management; that is, all the basic concepts adhere to the thinking principle of the mega infrastructure construction management theory.

1. Mega Infrastructure Construction-Environment Compound System. This concept abstracted the new compound system formed by the integration of the established mega infrastructure construction and the original engineering environment. In addition to the existing complex adaptive systems, i.e., the society, economy, and ecology, this system has increased the number of new complex artificial engineering entities. Therefore, because the systematic complexity of the compound system has been increased, especially during the long cycle, this system may evolve and produce new overall behaviors of the system and its functions that embody the systematic complexity of mega infrastructure construction management.
2. Management Complexity. This concept involves various types of complexity that are created by the mega infrastructure construction environment, the multiple subjects and their inadequate abilities, and the high integration of the engineering system. It also involves the mega artificial construction system, the complexity of the mega infrastructure construction-environment compound system, the complexity of the links, the main elements of the mega infrastructure construction management activities, and the overall complexity of the management activities. Accordingly, this concept sums up the main reasons for the complexity of mega infrastructure construction management and guides us to select different management plans for different complexity problems.
3. Deep Uncertainty. Deep uncertainty has not only profoundly revealed the important reasons for the formation of the environment of mega infrastructure construction management and for the complexity of problems but also exposed the characteristics of the subjects' behaviors with respect to mega infrastructure construction. More specifically, deep uncertainty is the direct or indirect reason for the complexity of mega infrastructure construction management. Thus, this concept further deepens the description of the essential attributes of mega infrastructure construction management.
4. Scenario. Scenario, as a concept, refers to the macro phenomena and the evolution of the phenomena formed by the mega infrastructure construction environment or the mega infrastructure construction-environment compound system, on an overall level, as well as the path that forms the phenomena. It is further noted that it is, at times, the mega infrastructure construction itself and man's

creative behaviors that created the scenario of complexity, a situation that further deepens our understanding of the complexity of mega infrastructure construction management.

In addition, the formation process of the complexity of the scenario determines that we cannot use traditional analyses or forecasting methods to study the general rules of the process. Rather, we should employ multidisciplinary integrated methods that include computer experiments. Accordingly, this concept will greatly enrich the methodology of the studies regarding the mega infrastructure construction management theory.

5. Subject and Core Subject. The subject of mega infrastructure construction is a subject group composed of multiple autonomous subjects. This concept emphasizes not only that the subject group of mega infrastructure construction management is a structured and stratified complex self-adapting system but also that the ability of the subject group is the result of the overall ability of the group under the dominance of core subjects. As such, it is evident that the complexity is the result of the abilities of the mega infrastructure construction management subjects.
6. Management Platform. With respect to practical management activities, the management subject group functions as a management organizer. However, due to the complexity of the management problems, rather than developing various management plans, the core function of the mega infrastructure construction management organization is to provide the necessary environment and conditions that enable the subject group to develop the ability and competences necessary to effectively control management complexity by building platforms. Moreover, the management platform has revealed the scientific connotation of the organization pattern of mega infrastructure construction management.
7. Multi-scale. With respect to the mega infrastructure construction management activities, a class of management elements that can distinguish the phenomena and characteristics of ordinal changes regarding a specific dimension that has important significance and can identify and analyze the complex structure of the management problems of mega infrastructure construction has been abstracted and refined.
8. Adaption. This concept focuses on the complexity of the behavior of the management subject. As such, it describes not only the subject's behaviors and features but also the overall degree of coupling between the main result of the subjective behavior (i.e., the proposed management plan) and the environmental complexity. Therefore, it fully highlights the most important basic principles of the subject's behavior and the quality of the behavioral result with respect to the mega infrastructure construction management activities.
9. Function Spectrum. The mega infrastructure construction itself and the complexity of the mega infrastructure construction-environment compound system have uncovered the severe complexity revealed by the function of mega infrastructure construction. For example, the mega infrastructure construction-environment

compound system simultaneously owns the structured constructive function, the semi-structured generative function, and the non-semi-structured emergent function. That is, it has the multidimensional characteristic of the functional structure and the multidimensional concept that reflects the ordered arrangement of the function types on the same dimension. Thus, the spectral degree is actually the description of the mega infrastructure construction functions and the targeted complex structure.

From this simple analysis, it is evident that the basic concepts presented herein are regarded as refinements that represent the abstractions of the crucial links of mega infrastructure construction management activities and the complexity attributes of the elements. As such, these concepts were not simply and directly borrowed from the present concepts of complex system science or the complexity of other disciplines. Because the related notions lack the true practical background of mega infrastructure construction management activities and problems, they lead to the tagging and "bubblization" of the concepts, a situation that loses the essential significance of establishing a mega infrastructure construction management theory concept system.

Moreover, the mega infrastructure construction management theory is the outcome of the theoretical thinking about management activities and problems, including the basic elements such as environments, subjects, objects, targets, and behaviors. Accordingly, it must obey the objective logic of activities, problems, and people's thinking logic. In other words, the basic concepts, as a theoretical system, cannot be isolated or fragmented. They should not only cover the mega infrastructure construction management activities and problems but also exhibit a close, logical correlation among those activities and problems. That is, within the theory system, the basic concepts should guarantee that the connotations are consistent with mega infrastructure construction management practice and that the concepts fully exhibit systematization and logicalization. Otherwise, people cannot form fundamental rationales or resolve scientific problems in the theory system on the basis of concepts and the combination of those concepts.

The logical correlations of the basic concepts are as follows:

1. The mega infrastructure construction-environment compound system equates to the abstraction of the mega infrastructure construction management object, including the environment and any relevant problems.
2. Management complexity is characterized by the abstraction of the common essential attributes of the mega infrastructure construction management subject, object, and environment. As such, management complexity has directly demonstrated the thinking principle of the mega infrastructure construction management theory.
3. Deep uncertainty refers to the abstraction of the features of the mega infrastructure construction subjects, behaviors, and environment. It also incorporates the refining of the justifications for the essential attributes of mega infrastructure construction management.

4. Scenario, as a concept, is the abstraction of the environmental features of mega infrastructure construction management, especially those features of environmental evolution.
5. The subject and core subject are the abstraction of the complex structure of the mega infrastructure construction subject group.
6. The management platform is an abstraction of the complexity of the mega infrastructure construction management organization function.
7. The concept of multi-scales is an abstraction of the behavior principle regarding mega infrastructure construction management subjects and the quality of the behavior result.
8. The concept of adaption is the abstraction of the basic principle of the mega infrastructure construction subject and the platform of the construction.
9. The function spectrum is the abstraction of the functions of a mega infrastructure construction artificial system and the complex structure of the subject's engineering goals.

It follows that these concepts involve the mega infrastructure construction management environments, subjects, objects, organizations, targets, thinking principles, and standards of conduct that envelop the key elements of mega infrastructure construction management activities, especially as they do not focus on the essential complexity attributes. However, given a certain logical association, these concepts can form a basic logical framework regarding the mega infrastructure construction management activities and problems, and they have presented a clear illustration of their respective functions and effects in the mega infrastructure construction management activity arena.

Therefore, the basic concepts as mentioned herein exhibit a systematic and logical quality that also serves as the premise and assurance of the quality of the mega infrastructure construction management theory system as established and presented within the context of this book (Fig. 5.5).

Finally, this chapter proposes nine basic concepts with respect to the mega infrastructure construction management theory system. However, this does not mean that these nine concepts are complete or that they are essential aspects of the mega infrastructure construction management theory system to be built. That is, the rationales

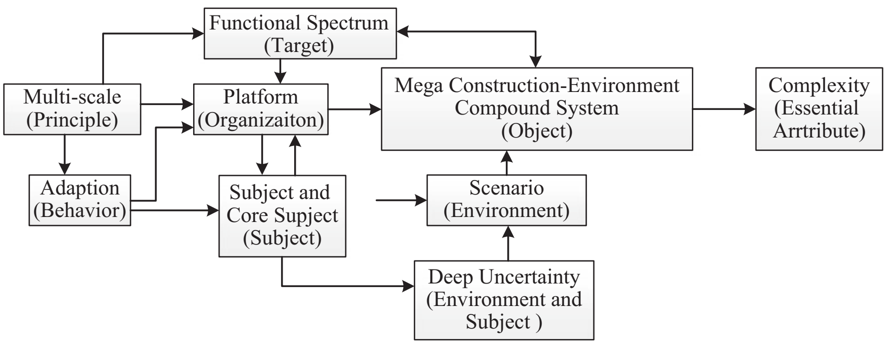

Fig. 5.5 The logicalization and systematization of the basic concepts

and scientific problems of the system consider the nine concepts as the foundation and deduce from those concepts those that are relevant. It is similar to the occasion where the mega infrastructure construction management system is built based on the nine pillars, but these pillars are considered only as follows:

1. The book is an exploration of the establishment of the mega infrastructure construction management theory system and an attempt to build a theory system from a certain perspective based on the engineering management practice. Henceforth, various scholars' increasing explorations and attempts will continuously enrich the basic concepts of the mega infrastructure construction management theory system.
2. The nine concepts are, to some extent, the most basic, conclusive, and inclusive concepts. Along with the continuous expansion of the theory system, especially with respect to the scientific problems of the theory system, some new concepts will be produced within the scope of specific scientific problems. The levels and structure of the concept system will be gradually enriched and expanded. For example, the concept of scenario robustness appears in the deep uncertain decision-making regarding scientific problems of the mega infrastructure construction and the concept of the strategy resource supply chain. These all indicate that the mega infrastructure construction management theory system has exuberant vitality.

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Chapter 6
Fundamental Principles Behind the Theory of Mega Infrastructure Construction Management

The fundamental principles behind the theory of mega infrastructure construction management encompass the basic maxims of the management subject's behavior and the operational rules for management activities, which is a summary of practical experience based on the management activities of mega infrastructure construction and the conclusion of logical reasoning according to fundamental concepts. In addition, the development of principles, especially the principle system, is an endlessly evolutionary and deepening process in need of long-term exploration and perpetual improvement. Thus, five fundamental principles are proposed in an attempt to formulate the theory of mega infrastructure construction management.

6.1 The Fundamental Principle of Complexity Degradation

Complexity, as stated in Sect. 2.3.4, is the essential attribute of mega infrastructure construction management. This signifies that regardless of the number of different forms and features of mega infrastructure construction management, the key to analyzing and solving problems is how to deal with and bring under control the complexity of those problems, that is, how to minimize the complexity from the perspective of thinking. Accordingly, the basic behavioral maxim for the management subject to analyze and solve problems should be complexity degradation.

6.1.1 The Fundamentals of Complexity Degradation

Because it is a uniquely prescribed complex engineering concept that is composed of material resources, mega infrastructure construction naturally manifests the physical complexity that is derived from engineering substantiality. The complexity

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of such a real, certain, and actual engineering substantiality is also real, certain, and actual. In fact, any real substantiality regarding mega infrastructure construction evolves step-by-step from an engineering concept to engineering substantiality and from the abstract cognition of attributes of physical engineering elements and the association between them to a real engineering concept.

As a consequence, in the abstraction phase of engineering and cognition, human beings' activities are undertaken primarily at the thinking level. During this phase, based on theoretical thinking, attributes of the hard engineering system are abstracted and then systematized together with their associations, which results in a logical system characterized by the attribute of complex engineering, also known as *engineering insubstantiality*. Apparently, in contrast to the physical complexity of mega infrastructure construction substantiality, mega infrastructure construction insubstantiality is characterized by systemic complexity with attributes of engineering elements. In this way, by making the attributes of engineering elements logical and systematic (Morris and Hough 1987; Miller and Lessard 2000; De Bruijn and Ten Heuvelhof 2000; De Bruijn et al. 2002), engineering insubstantiality enriches the management subject's understanding of the holistic attributes and functions of mega infrastructure construction, supports the subject in developing a plan to establish engineering substantiality, and directs the activities of mega infrastructure construction management by inferring the association and causality of attributes between engineering elements.

In addition, because engineering insubstantiality encompasses the logical system of the attributes of engineering elements and the association between them is established in accordance with theoretical thinking, man's individualized value orientation and cognition, to a great extent, will impact and determine how to abstract attributes of engineering elements and ascertain the association between them. That is, even the forms of physical complexity regarding the same engineering may result in various insubstantial engineering elements due to the subject's various modes of thinking. On the premise of not changing the inherent complexity of engineering, the variability manifested in the process of developing insubstantial engineering can be exploited to design a certain type of technical path that reduces and decomposes the inherent complexity of the engineering. In particular, conducted in connection with the abstract attribute of engineering elements and the association among them, this type of reduction and decomposition, in many cases, only manifests a conceptual and logical form more similar to the "talking about stratagems on paper—empty talk" philosophy of ancient China or "war deduction" of modern China, and thus, it indeed has not exerted any impact on or destroyed the objective and inherent engineering complexity. However, in a certain sense of granularity and performance, it helps us to understand and analyze the inherent engineering complexity that is difficult to comprehend and understand in a clearer and simpler manner.

Thus, in actual activities of engineering management, especially in the phase of engineering substantiality concreteness, the management subject must still confront the inherent attributes of mega construction substantiality and the relevant associations (Corbett et al. 2002; Pheng and Chuan 2005; Leung 2007), particularly those major associations that play a decisive role in the physical complexity of mega infrastructure construction. Hence, no actual activities regarding mega infrastructure construction management can depend only on the concept, hypothesis, and general logic of insubstantiality thinking or only on the aforementioned complexity thinking of reduction and decomposition. Rather, they must rely on substantiality thinking to integrate all attributes, associations, and inherent complexities of mega infrastructure construction to realize complete engineering substantiality.

This signifies that, regarding the process of understanding and analyzing the attributes and associations of the elements of mega infrastructure construction, the management subject should make the best use of the cognitive variability exerted by the logical system of attributes and associations of engineering elements on the managing complexity of mega infrastructure construction, then properly and reasonably reduce and decompose systemic complexity (*complexity degradation*) at the level of cognition through viable paths, and finally help determine the laws and principles behind the complexity. This is, of course, a hypothetical and idealized thinking adopted to enhance the management subject's cognitive abilities within the insubstantial logical system (Corbett et al. 2002; Chu et al. 2003; Jones and Anderson 2005; Heal and Kunreuther 2007; Fang and Marle 2012). It is, furthermore, a means to support the management subject's cognizance of the complexity, and as such, it aims to help the management subject overcome difficulties in perceiving the complexity of the management activities, to remedy the lack of perception on the part of the management subject, and to comprehend the laws regarding the management of complexity.

Furthermore, in actual activities of mega infrastructure construction management, the management subject must employ substantial thinking to face the physical substantiality of concrete engineering, to restore its genuine complexity, and to prevent any substantive physical damage or harm to the complexity of the substantiality of mega infrastructure construction due to insubstantial engineering thinking. Thus it is evident that both insubstantial thinking and substantial thinking play pivotal roles in the building and management of mega infrastructure construction.

Hence, one can see that the process of complexity degradation must give full expression to and guarantee the principles of integrating insubstantial thinking with substantial thinking, of combining the individualized characteristics of mega infrastructure construction with the general law of attributes, and of developing a comprehensive and integrated thinking with respect to activities of mega infrastructure construction management. *On the whole, and based on the variability of mega infrastructure construction insubstantiality, to hypothesize and idealize degradation behavior is to assist and stand by the management subject's cognition and analysis of managing complexity. In the later phase of the actual activities of mega infrastructure construction management, to restore the inherent physical complexity of engineering is to ensure the authenticity and completeness of mega infrastructure construction substantiality. This is the fundamental principle of complexity degradation.*

It can be proposed that the principle of complexity degradation is the principal code of conduct and the guiding objective for the management subject when encountering complexity problems in mega infrastructure construction management activities. To be specific, the principle of complexity degradation can be understood from the following three aspects:

1. The "reduction behavior included in degradation focuses on enhancing the subject's ability, for instance, to analyze and control the complexity through active learning. By now, it is feasible to completely maintain the original and intrinsic form of the physical complexity of engineering. In that way, what "reduction" embodies, in a certain sense, is more of "holism" thinking" (Smuts 1926).
2. The decomposition behavior included in degradation, with the aim of reducing the original complexity, places greater emphasis on the partitioning of the original, intrinsic, and holistic physical complexity of engineering at the level of insubstantial thinking. Consequently, decomposition embodies reductionist thinking (Oppenheim and Putnam 1958; Nagel 1979; Auyang 1998).
3. Whatever the case, it will not cause real harm to the original and intrinsic physical complexity of engineering but assist the management subject to enhance the ability to analyze and control the complexity. In the meantime, it is noted that regardless of which degradation behavior the management subject employs, the intrinsic engineering complexity cannot be lost, nor can its characteristics be changed qualitatively.

6.1.2 Basic Degradation Paths

As previously mentioned, complexity is the essential attribute of mega infrastructure construction management. This complexity is a form of integrated and holistic cognition in that it integrates multifarious and multi-level complexities of the environment, organization, subject, and problems related to the activities of mega infrastructure construction management, and it is also the reflection of the physical and systemic complexities of mega infrastructure construction in the management realm. With respect to the fundamental thinking of management, mega infrastructure construction management is primarily the management subject's management of complexity. Hence, it is doubtless that the management subject expects the management problems to be easier and less complicated. However, management complexity is the management subject's cognition of the inherent attributes of mega infrastructure construction substantiality from the perspective of mega infrastructure construction insubstantiality as well as the reflection of the intrinsic complexity of mega infrastructure construction in the management subject's mind. As a result, the management complexity will inevitably vary among the various management subjects and according to the subject's developing cognitive competence. This suggests that there exists a variety of complexity degradation paths in the practical process of complexity degradation.

A crucial and pivotal issue regarding complexity degradation behavior is how to design specific degradation paths and how to ensure the propriety of the degradation and be as appropriate as possible based on the sources and causes of complexity. The following represent several possible paths.

1. *The Degradation Path of Enhancing Management Subject's Cognition*

There are two major origins of the complexity of mega infrastructure construction management. The first is ontology, that is, complexity arises out of the management environment and its problems, and the second is subjectivism, that is, complexity arises from the management subject's cognitive defects, including the lack of knowledge, experience, and ability. With respect to the relation among substantiality, complexity, and the subject's cognition, once the subject's cognitive ability is enhanced, the complexity of the problems is reduced.

The subject's ability to manage complexity is dependent on the subject's learning ability because comprehending management complexity, controlling management problems, and enhancing management ability are the results of the subject's cognition of the objective management complexity of mega infrastructure construction. Consequently, self-learning is a vital path for enhancing the management subject's cognitive ability and reducing the complexity of the problems.

The management subject's self-learning refers to the subject's initiative to acquire all necessary knowledge through a variety of approaches and means and to transform that knowledge into enhancing his ability to analyze, predict, and control the complexity of problems. In this process, the management subject's self-learning should be extensive and comprehensive enough to incorporate not only natural science and engineering technology but also economic management, laws, regulations, philosophy, and history. The subject of self-learning includes management individuals and the management subject group as well. To form an enduring and effective self-learning mechanism for the management subject group of mega infrastructure construction, it is essential to devise an organizational pattern conducive to promoting the self-learning of the management subject group and, more importantly, the core subject.

Mega infrastructure construction management organizations in China are generally staffed with technical consultants and panels of experts. They also engage successful overseas companies and experts as part of a think tank to analyze and settle complex engineering problems. This constitutes an effective organizational pattern for the management subject's self-learning.

Taking the Hangzhou Bay Bridge over the East China Sea as an example, in the preliminary demonstration stage, technical consulting was widely used for determining the location for the bridge and the programs to be adopted to manage bridge type, infrastructure, and cost-effectiveness.

In August 2002 and again in 2004, during the preliminary design stage of the bridge, relevant units consulted with T.Y. Lin International Inc. regarding the anticorrosion of the steel pipe pile, the durability of the concrete, the construction of the bridge's superstructure, and the mat formation of the steel bridge floor. In July 2003 and September 2004, these units also consulted with Deng Wenzhong, a world-renowned bridge architectural master and academician of the National Academy of Engineering, USA, regarding the anticorrosion of the prestressed concrete box girder and the structural system of the cable-stayed bridge. These consultants offered significant intellectual support regarding these complicated technical management problems.

In addition to enhancing the management subject's ability and reducing complexity by means of self-learning, it is also possible to obtain richer information resources through modern information technology and thus reduce the complexity of problems arising from information loss and the lack of information processing capacity.

In effect, activities of mega infrastructure construction management require, simultaneously, logical thinking, image thinking, and inspirational thinking as well as integrated complexity thinking, which is the result of the first three types of thinking. When it comes to resolving complexity problems, mankind has major advantages with respect to image thinking, epiphany, experience, and creative thinking. Nonetheless, these advantages increasingly depend on the gathering, processing, storing, and transmission of information. Only by relying on these processes can we take advantage of the information and the findings resulting from analyzed information in an accurate and real-time manner and improve the management subject's ability to manage complexity problems in combination with their own experiences, knowledge, and wisdom.

Thus, it can be inferred that the management of information resources and the capability of resource management can effectively reduce cognitive errors caused by man's psychological and physiological factors; overcome the cognitive limitations resulting from man's experiences, personality, feelings, modes of thinking, and values; and help to achieve the management subject's goal of reducing complexity via information technology.

2. *The Degradation Path of Improving Management Methods*

The improvement of management methods can degrade complexity, as demonstrated by the following:

1. Compacting and Coordinating Management Objectives

That fact that diversified management objectives of mega infrastructure construction can lead to management complexity is demonstrated through the following aspects: (1) multi-level and diversified management objectives, (2) contradiction and conflict between management objectives, and (3) changes in the management subject's values that result in the dynamic nature and complexity of management objectives.

Given these circumstances, compacting and coordinating management objectives can reduce management complexity.

Compacting management objectives refers to, on the basis of objective design, sifting, merging, and extracting constructive, generative, and emergent objectives of mega infrastructure construction to highlight and guarantee the status of strategic and fundamental objectives.

For instance, it is necessary to establish a hierarchy of management objectives of mega infrastructure construction. Engineering objectives are hierarchical such that the strategic engineering objective at the top of the hierarchy reveals the overall objective and significance of the engineering, whereas the objectives that follow are tactical and executive in nature and thus, respectively, indicate the domain objective and the implementation plan or measures for the engineering.

The superior objectives of mega infrastructure construction are generally abstract, macroscopic, and not completely predictable, whereas the inferior objectives are more concrete, microscopic, and predictable.

In addition, mega infrastructure construction management must take into account the unity of opposites of all compact objectives. The *coordination of management objectives* of construction management is based on the compacting of the management objectives of mega infrastructure construction management and is intended to eliminate, restrict, and compensate for partial objectives, to maintain a balance among all objectives, and to coordinate the direct objectives with the indirect ones, the short term with the long term, and the functional with the social and the strategic.

2. Compacting and coordinating management objectives, to some degree, compresses the diversification of objectives and strengthens the structural association among the objectives. Thus, it is conducive to lessening the orderliness and measurability of management objectives, as doing so reduces the complexity of analyzing and evaluating the objectives.

Additional details regarding the compacting and coordinating of management objectives are presented in Sect. 6.2.

3. Condensation of Future Construction Scenarios

The concept of scenario tells us that the future scenario space of complex systems is sufficiently large. In this space there exist not only imaginable scenarios but even scenarios that are unthinkable or unimaginable for the management subject. Furthermore, it is impossible to predict the occurrence of any future scenario, and it is also difficult to predict how a scenario will evolve from a present real scenario into a future scenario.

In this case, the general evolutionary relation between the present reality scenario and the future scenario of mega infrastructure construction can be explained as follows. A scenario dot follows a certain path of an uncertain and fuzzy beam of paths and evolves into some uncertain scenario dot in the sufficiently large scenario space. Transitioning from the present to the future, first, there must be a scenario dot in the future, though in the present, it is difficult to ascertain and predict which scenario dot it is. Second, it is difficult to ascertain and predict which path is the evolutionary path from the present scenario dot to the future scenario dot. Even under these circumstances of uncertain scenario and evolutionary path, however, we must accomplish the management task of mega infrastructure construction, which is evidently an extremely arduous task. What is even more arduous is that, as the future becomes increasingly more distant, the corresponding scenario space becomes ever larger, and the future scenario dot and corresponding evolutionary path become ever more bifurcated and fuzzy, thus giving rise to greater management complexity.

We cannot eliminate this objective condition, as it is caused by the multi-scale characteristic of mega infrastructure construction and the complexity of the multiplex system of the mega infrastructure construction and its environment. Given such breadth and depth, man cannot completely ascertain all of the possible scenarios and behaviors and translate them from the present to the future.

Therefore, we adopt the following methods, listed below, to facilitate the process:

1. Target certain concrete scenarios with particular meaning in the future scenario space according to the experiences and knowledge of the management subject group.
2. Regard the future scenario as a forecast for the state of the environment and generate the future scenario by establishing specific conditions and parameters.
3. Define a subspace within the future scenario space and reasonably believe that the possibility of the future scenario appearing in the subspace is much higher.
4. Set certain scenarios with special meaning as the threshold value of the future scenario; in other words, any scenario confined in a small area close to the threshold value is either acceptable or unacceptable.

All of these methods attempt to condense the deep uncertainty of the future scenario space of mega infrastructure construction with the goal to reduce management complexity.

1. Comparison and Iteration of Managing Programs

Among the challenges to the management complexity of mega infrastructure construction, one is the difficulty in determining the technical path of managing programs. For instance, the determination of the preliminary management and construction of programs for mega infrastructure construction involves multiple objectives and subjects; touches upon the integration of technology, funds, equipment, and personnel; and relates to engineering, social, economic, and cultural fields. Furthermore, it incorporates regular patterns of engineering, regular patterns of technology, regular patterns of management, and regular patterns of humaneness.

At this point, the management subject can repeatedly compare and adjust paths to bring them closer and break down the integral complexity of problems into a staged, multi-field, relatively simple problem that can be analyzed and managed, which then leads to an ultimate solution.

This fundamental principle is further elaborated in Sect. 6.4.

3. *The Degradation Path of Dissecting Association*

We first expound the management complexity arising from the strong association among the elements of mega infrastructure construction and the higher integration of management elements.

For general construction, the principal relation between management elements is hierarchical, the transverse association is relatively weak, and the management objective is generally predictable and realizable. Given such a circumstance, causality in construction management is, in general, evident and direct. Transversely, construction management can be decomposed into a certain number of relatively independent parts such that construction complexity can be confined to relatively independent parts and be easily divided into relatively independent management functions. This situation, on the strength of reductionism, can facilitate the decomposition of direct management objectives on the basis of quality, progress, and cost as well as propose solutions to parts of problems or for each management functional field through an effect analysis technique that is similar to that of the failure mode and the analysis technique for risk factors. The ultimate result is the resolution of integral complex problems by means of iteration.

However, mega infrastructure construction is the integration not only of hard resources, such as materials, equipment, funds, and techniques, but also of soft resources, such as organization, management, information, and values. Hence, the integration of all parts of mega infrastructure construction is heightened, and the transverse interaction between all parts is strengthened such that it is even stronger than the interaction between the vertical hierarchies of the mega infrastructure construction. As for influence, the mutual effect of certain elements is no longer partial but rather more likely to be total, and as such, it can gradually spread to become a holistic behavior that dominates the overall situation. At this point, the functional design of the mega infrastructure construction is no longer completely predictable, and its causality is not as direct and evident as before.

For example, due to the heightened integration of the elements of mega infrastructure construction, minor changes in engineering elements may be magnified, thus leading to consequences at large and causing failures to result in accidents. This is the primary reason that the causality of the risks of mega infrastructure construction becomes fuzzy, that the risks are unforeseeable, and that problems continue to erupt from time to time. This type of management complexity, which is caused by the strong association among the heightened integration of mega infrastructure construction elements, is referred to as *association complexity* in the field of mega infrastructure construction management. Because it is obvious that the association complexity of mega infrastructure construction has reinforced management complexity, it is advisable to dissect the association between the parts and the whole of mega infrastructure construction to reduce management complexity.

As to how to dissect the association between management elements of mega infrastructure construction, equal emphasis must be placed on both theory and experience, and the main train of thought should be as follows. First, it should be realized that association dissection is nothing but the management subject's dissection of subordination association, inclusion association, juxtaposition association, causality association, and dependence association among the attributes of construction insubstantiality via a topological structure or logical structure. Moreover, it is a type of hypothesis and idealization in cognitive thinking, rather than a dissection of any inherent physical complexity of mega infrastructure construction substantiality.

Before dissecting the association between the management elements of mega infrastructure construction, it is necessary to analyze the association of the attributes in accordance with the following principles:

1. With respect to one class of association whereby the circumstances in the association network are relatively weak, we can dissect at the point of weakness. As the complexity of each dissected part is bound to be reduced, we can assemble all of these parts to restore the former system (as represented in Fig. 6.1).

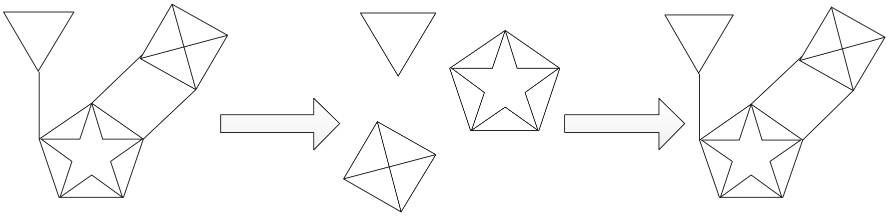

Fig. 6.1 Dissection and assemblage of parts in the association system

2. As to the other class of association situations that do not exhibit a relative weakness, it is advisable to simplify and strengthen the association pattern, to dissect the association covertly, and to reduce the complexity prior to synthesis.

These two principles constitute the process of association—dissection—reassociation. In this circumstance, the management subject attempts to decompose the integral management complexity of the mega infrastructure construction, which is perceived as the whole of a sophisticated machine, into many parts with lower complexity, i.e., different parts of the machine, and then, by analyzing and studying the complexity of these parts one by one, they can be reassembled to recreate the original machine, i.e., the process of association restoration.

Regardless of the dissection method adopted, it is, under no circumstances, permissible to substantively decompose or destroy the physical association of the management elements of the activities of mega infrastructure construction management, as doing so will destroy the intrinsic management complexity of mega infrastructure construction.

6.1.3 The Degree of Complexity Degradation

During the course of complexity degradation, one vital, albeit thorny, issue is when to terminate the degradation process, supposing that the management subject adopts the technique of complexity degradation. In other words, how do we contain degradation behavior within acceptable limits?

At present, it is difficult to seek and find a quantifiable solution to this issue. Just as it is difficult to quantify and measure the complexity of management problems with respect to mega infrastructure construction, it is also difficult to measure the efficacy of complexity degradation and, accordingly, arrive at a definitive judgment about when to cease degradation. All in all, the research on the appropriate degree of complexity degradation as it pertains to mega infrastructure construction management is exceedingly embryonic in theory. Therefore, we briefly analyze this issue from the connotation of complexity degradation.

First, any type of complexity degradation can by no means degrade system complexity into general systematicness or simplicity; that is, the thinking mode of reductionism cannot be blindly employed to degrade complexity.

Second, complexity degradation is a supplementary means to aid the management subject in cognizing and analyzing management complexity at the level of construction insubstantiality. Thus, providing the management subject is capable, or becomes capable as a result of self-learning, of controlling the complexity; it is the right time to cease degradation. Then, in the event that the management subject discovers he lacks the requisite ability, the degradation can be reinstated. However, the management subject's capability to restore the original inherent complexity during the process of the step-by-step degradation must be considered.

More specifically, it is crucial to acknowledge that the consequences of complexity degradation are not all positive in that, with respect to practical construction management activities, in the wake of degradation, the subject not only must restore the degraded insubstantiality complexity to the construction's natural form of original intrinsic complexity but also must compensate for the cognitive damage that occurs due to the degradation. All these adverse degradation behaviors are complicated and may, at times, be even more difficult to manage than the degradation itself. In addition, the more that is degraded, the more difficult the restoration will be.

Not all degradation behaviors are efficacious, nor do they all lead to the desired result. As stated in Sect. 5.1.2, the goodwill or original intention to degrade complexity can, at times, lead to a new type of complexity or even result in newly emerging, more severe, and more complicated consequences due to a lack of estimation of and precaution against such complexity.

Practice has revealed that in actual management activities, the management subject is more apt to rely upon his own adaptive self-learning ability, to determine which degradation method to employ, and to determine when to effectively cease the degradation by managing the consensus-reaching process of the subject group.

When the method of complexity degradation of mega infrastructure construction management and the degradation degree has been defined, another crucial problem that must be addressed is the effectiveness of the complexity degradation of mega infrastructure construction management. As previously mentioned, the timing criterion refers to the period when complexity degradation is effective. This criterion is of great practical significance to mega infrastructure construction management. If the complexity degradation is improper or ineffective, it is either because excess degradation transformed the original intrinsic complexity into a too simplistic issue or into general systematicness or because insufficient degradation makes it difficult for the management subject to manage the complexity. This problem is not only pivotal for the rationale behind the management theory of mega infrastructure construction but also a fundamental scientific problem in the management theory system.

Finally, consistent with the above discussion and with the classified concepts of complexity degradation of mega infrastructure construction management, as discussed in Sect. 2.3.4 (Figs. 2.2 and 2.3), we can, in principle, expound the degradation degree of complexity as it relates to mega infrastructure construction management.

In the case where problems in Category A are degraded to those in Category B or Category C according to the classification of problems regarding mega infrastructure construction management, or where problems at the top level are degraded to those at the second or third level according to the problem system of mega infrastructure construction management, the complexity of matter generally has a basic structure. Thus, even if there exists a dynamic property and uncertainty, the emergent property and deep uncertainty are not the dominant factors. Accordingly, this issue can generally be managed by the integrated technique for prioritizing project management. For instance, based on the design and decomposition of the engineering function spectrum, the preliminary project approval, and the demonstration of mega infrastructure construction, which is a matter of complexity management, the problem can be decomposed into dozens of relatively independent and simple subtopics, and their associations can, hence, be simultaneously considered. As long as the problems within each subtopic can be resolved within the technique category of project management and the general system, the degree of complexity degradation of the project demonstration is appropriate. In another example, the bid division represents a complexity issue for mega infrastructure construction. The establishment of a large holistic bid division is complicated and requires the contractor to possess outstanding all-round competences. Given such a situation, to divide the holistic bid division into smaller segments represents a complexity degradation method. However, it also results in increased coordination among the connectors and interfaces of bid division and the contractors. In this case, the contractor's ability to control the complexity of the small bid division, as well as the difficulty associated with coordinating the complexity between the connectors and the interfaces, must be considered. Thus, the solution is to ensure that contractors can perform and accomplish the tasks within the category of project management and can also balance these two aspects.

Generally speaking, complexity management problems arise during the early and early-middle stages of the project, whereas in the late-middle and late stages of the project, the complexity of management problems, as a whole, continues to decrease. Hence, in the early and rather concentrated course of complexity degradation, to degrade issues of complexity so they can be addressed within the category of project management is exactly the effective and proper degree of complexity degradation.

6.2 The Fundamental Principle of Adaptive Selection

6.2.1 The Scientific Connotation of Adaptive Selection

In an ordinary sense, selection is the basic form of mega infrastructure construction management activities, and it is also the most common and most elemental behavior of management subjects at the operational level of management activities. Typical selective behavior consists of the selection of decision programs, organizational modes, contractors, suppliers, etc. (Chua and Li 2000; Jap and Naik 2008; Cheng et al. 2010; Mahdavi and Hastak 2014; Ballesteros-Perez et al. 2015; Awwad 2016; Asgari et al. 2016). It is necessary to realize that all acts of subject selection are performed in an environment of deep uncertainty and under complex circumstances with objective problems. As a consequence, the subject must return to construction substantiality thinking of complexity degradation from construction insubstantiality thinking of complexity, and this must comply with the adaptation criterion with respect to the subject's realistic behaviors.

The subject's selection behavior based on the adaptation criterion is known as adaptive selection. Briefly stated, adaptive selection is the subject's behavioral reality at the operational level of management activities.

What constitutes the scientific connotation of adaptive selection?

First, adaptation is the objective of the subject's selection behavior. Owing to the existence of the many forms and types of complexity embodied in the problems and environment of mega infrastructure construction, the subject must replace the conventional thinking of objective optimization with the new thinking of objective adaptation (Williams 1999; Li et al. 2009; Xia and Chan 2012; Owens et al. 2012). As for complexity, adaptation is optimization. For example, a project decision program that is adaptable to changes in the deep uncertainty scenario is optimal, and the flexible organizational mode that is adaptable to the complexity of different management issues is the most effective. Undoubtedly, with adaptation as the objective, the subject's subjective value preference, to a great extent, will be implanted, thus causing selections to become a bit convoluted. To manage this problem, the subject's adaptive self-learning ability and cognitive and analytical abilities should be enhanced, and it must be acknowledged that selection is an ongoing process of trial and error, iteration, and approach, and as such, it cannot be accomplished in one stroke.

Second, adaptive selection is the compensation for complexity degradation offered by the subject at the operational level. Complexity degradation is the lowest-level thinking principle and the guiding objective for the subject to confront management complexity. However, degradation is merely an insubstantial hypothesis that manifests itself during the subject's problem cognition and analysis process. That said, in actual mega infrastructure construction creation activities, the innate construction complexity remains. Thus, on the occasion when the subject confronts real complexity and must decide on the management program and manage problems, he must restore the objective construction complexity from insubstantiality to substantiality or adjust his own behaviors. Whether it is objective restoration or subjective adjustment, the subject's limited rationality determines it to be a selection process complete with unceasing trials and errors as well as revisions. This is because it is only through repeated selection that a cognitive sequence approaching the real complexity of issues gradually takes form and allows for problem-solving program to be established and reorganized consistent with the sequence. Hence, it is assumed that adaptive selection is the compensation and restoration of complexity errors and damages caused by complexity degradation to the subject's cognition.

Third, adaptation symbolizes the subject's code of conduct and behavioral capacity with respect to his own selection process. To control management complexity and tackle complexity management problems, the subject is required to accumulate experience and enhance his abilities through his own adaptive learning behaviors. Thus, the subject's adaptive self-learning is the prerequisite and the premise for his adaptive selection as well as a significant symbol of the subject's capability. In accordance with the theory of system science, any mega infrastructure construction management program is a complicated system devised by the subject, and as such, it contributes to polytype and multilayered complexity. This is the subject's active reaction to the complexity of mega infrastructure construction management issues and includes antedating reactions. Moreover, it is the basis for the subject and the complexity to couple with each other to shape the holistic behavior of management activities. Consequently, the subject should, on the strength of adaptive self-learning, ensure feasibility and other qualities of the program by comparing and sifting the complexity of programs. In this way, when selecting the program for mega infrastructure construction complexity issues, the subject will naturally follow the adaptive self-learning path, which is precisely the fundamental connotation of self-learning behavior in the course of the subject's adaptive selection.

In this case, adaptive selection has been the most vital practical operation mode for the subject in mega infrastructure construction management activities and one of the fundamental rationales for mega infrastructure construction management activities. If it is related to the rationale of complexity degradation, both rationales center on the subject's behavior and together form a new and comprehensive code of conduct for mega infrastructure construction management activities. Consistent with the code of conduct, degradation facilitates the subject's cognition and analysis of construction management complexity at the thinking level through virtualized construction substantiality, and selection then helps the subject return to substantialized practice from the virtualized thinking at the operational level. In this way, the subject not only takes advantage of cognition inspired by the degradation thinking but also avoids possible cognitive errors caused by virtualization at the operational level. This is, in a sense, the shaping of systematology from system science via the integration of reductionism and holism, which then gives expression to complex holism.

Adaptive selection is applied widely in other fields of management science, such as natural resource planning and management, in which the subject acquires new knowledge through the adaptive self-learning process that is then applied to improve management policy. For example, the Ministry of Forests in British Columbia, Canada, surmises that the essence of adaptive selection management is to learn and obtain information from the results of natural resource management, to decrease the uncertainty of management step-by-step, and to facilitate the process of constant adjustment of management policy and practice. The American Forest Ecosystem Management Assessment Team (FEMAT) contends that adaptive selection management is the process of regarding decision implementation as a scientific management experiment and then applying the experimental results to test the hypothesis via the management plan and forecast authenticity. Parma (1998) holds that adaptive selection management refers to formulating management policy and plans based on an existing knowledge of the system and preliminary management practice and then implementing strict management in accordance with the plan. Adaptive selection management, therefore, can be described as the acquisition of new knowledge from the experiment of decision implementation and be summarized as learning by doing or learning from management.

However, different from the adaptive selection method that places emphasis on policy formulation and updating, mega infrastructure construction management must respect the irreversible law of engineering construction (Morris and Hough 1987; Miller and Lessard 2001; Flyvbjerg et al. 2003; Williams 1999, 2005; Meier 2008), stress the onetime successful creation, and not allow the repeated process of "crossing the river by feeling the stones" or starting over, which is allowed by natural resource planning and management. Hence, the rationale of adaptive selection in mega infrastructure construction emphasizes that through repeated deliberation, analyses, simulations, and experiments, it, i.e., adaptive selection, is necessarily based on adequate adaptive self-learning, and thus, it eventually establishes a complete program at onetime and never results in major changes at the critical management stage, such as the occasion when proposing important management programs. This definitely doubles the difficulty regarding the subject's selection behavior with respect to strengthening self-learning.

In the practice of mega infrastructure construction management, adaptive selection can be divided into passive adaptive selection and active adaptive selection.

As presented in Fig. 6.2, passive adaptive selection means to start from an alternative program and transform it into a satisfactory program through the subject's adaptive self-learning of analysis, simulation, and correction. In the construction practice, the passive adaptive selection usually appears when a certain alternative program has been determined but still requires partial correction.

As presented in Fig. 6.3, active adaptive selection means to begin from several alternative programs and to establish an alternative program as the final satisfactory program through the subject's adaptive self-learning of comparison, sifting, and correction. In construction management practice, active adaptive selection is widely used and often employed when several rather different programs that must be compared at the same depth appear at the same time (Shenhar 1993; Gersick 1994; Loch et al. 2006; Van de Ven 2007; Shenhar and Dvir 2007; Mackenzie and Davies 2011; Edmonson 2012).

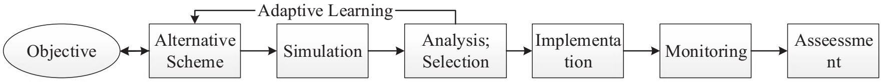

Fig. 6.2 Passive adaptive selection

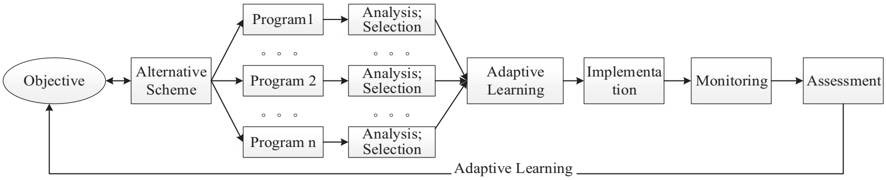

Fig. 6.3 Passive adaptive selection

6.2.2 Management Strategy for Adaptive Selection

After clarifying the connotation of adaptive selection, the major issue is to devise an adaptive path that will lead to identifying a strategy for adaptive selection behavior. In general, adaptation is the measurement of the self-adaptive attribute formed by critical behavior, such as the subject group's (management organization) selection of management objectives, the formation of the management program, and the assessment of the organizational mechanism for management and program adaptation. As a result, heightened adaptation demands an optimal design and arrangement of these types of behaviors, which specifically consist of the following three aspects.

1. *Adaptive Selection of Management Objectives*

In practice, the goal of the subject's adaptive selection is to successfully achieve management objectives, a process that relies on the objective spectrum structure of mega infrastructure construction and on subject preference. Because the management objective of mega infrastructure construction has a strong preference for and reflects the subject's interests and values (Li et al. 2009; Owens et al. 2012; Xia and Chan 2012), the same subject may establish various objectives but give them different weights even when facing the same construction. In this way, despite being scrutinized seriously and deliberately, the management objective proposed by the subject in management activities is nothing but the subject's selection result, which is based on a limited rationality at some stage or on a set of objectives proposed individually by different subjects. As such, adaptive selection should be applied to the objective set to resist the impact exerted by the defects of the objective set, e.g., incomplete objectives, poor hierarchy, limited relevance, and a lack of pretreatment of conflicting objectives, on the assessment of the overall management objective of engineering.

First and foremost, it is critical to reasonably screen and merge these objectives and to single out the most essential core objective on the strength of its extensive objective design. To select and construct a multi-objective system is, rather than the superimposition of multiple objectives in a general sense, to further reveal the complex association of the multi-objective system and thus gain a profound understanding of the physical complexity and the systemic complexity of engineering and synthesize the objectives. The challenge during the process of synthesizing objectives is to coordinate conflicting objectives. To this end, the key to screening the objectives is to scientifically discern the objective system, that is, to discern precisely the following:

1. Objectives are diversified.
2. Objectives are hierarchical.
3. Objectives are interrelated.
4. Objectives cannot be superimposed.

Non-superimposition means that although some objectives have the same attribute, the attribute cannot be superimposed. For example, the sum of many risks cannot be considered as a single large construction risk. Furthermore, objectives with various attributes cannot be superimposed either. For instance, it is not possible to superimpose the quality objective of engineering onto the safety management objective.

Furthermore:

5. Objectives are dynamic.
6. Objectives are balanced.

The structure of the objective system should be stable and balanced, as excessive concentration on one objective may be detrimental to the other objectives and ultimately negatively impact the achievement of the overall objective.

Finally:

7. Objectives have priority.

In the objective system, objectives from different hierarchies are of different significance, and the objectives in the same hierarchy are also of different significance at different stages. Thus, priority can be given to objectives of greater significance. At the macro level, the adaptive selection of objectives must comply with the following two principles:

1. Local objectives must be subordinated to the global objective.
2. The objectives must be attainable in terms of both technology and management.

At the micro level, the adaptive selection of objectives is appropriate for the following tasks:

Objectives of greater significance:

1. A correlation analysis that analyzes the positive correlation, negative correlation, superimposition, hierarchy, and association of objectives according to their nature and correlations
2. A conflict analysis that determines whether objectives conflict with each other and whether conflicting objectives can be coordinated, if so, how they can be coordinated
3. A time analysis that analyzes objective classification and its importance on different time scales
4. A resource analysis that analyzes resource consumption and the costs to achieve objectives
5. A profit analysis that analyzes the profits when the objectives are accomplished
6. A risk analysis that analyzes the relation among the objectives and the risks they pose for construction management, focusing on objectives that are easy to change, that reduce risks, and that decrease changes

The adaptive selection of objectives requires the subject to acquire more information and knowledge and to enhance his ability to analyze objective complexity through self-learning.

For example, when drafting the progress control program for mega infrastructure construction, the subject must coordinate conflicting objectives such as work hours, work efficiency, quality, and speed, a task that requires the subject to continue learning, enriching, and mastering the following information and knowledge:

1. The common rule of engineering construction of the same category
2. The actual progress and progress control experiences of domestic and foreign established construction of the same category
3. A comprehensive analysis of automatic control conditions for the construction to be built
4. A comprehensive risk analysis of the technology to be employed
5. A comprehensive balancing of the major direct objectives of the construction to be built
6. The overall consideration and assessment of the expectations of the construction's stakeholders
7. The development of the construction schedule, which is a vital resource

Accordingly, it is evident that, even though the direct representation of the schedule control of construction is time, when designing the schedule control program, the subject must consider not only the control tasks, including the risk, quality, investment, and safety of the construction, but also the construction subject group's value preference at a higher level to adequately ensure the comprehensiveness of the objective to control the construction's schedule.

Thus, it can be inferred that the managing complexity of mega infrastructure construction requires the subject to take into consideration the following aspects when devising the objectives for the management program:

1. Changes in the management environment will result in changes in management objectives.
2. Changes in the management subject's value preference will result in changes in management objectives.
3. Changes in the subject's cognition and ability to establish programs will lead to changes in management objectives.

In other words, it is evident that, for various reasons, the management objectives of mega infrastructure construction will change. To effectively deal with this, the subject must make adaptive adjustments to the objectives to exclude the possibility of invalid or faulty management programs.

2. *Adaptation Mechanism for Management Organization*

In accordance with the aforementioned analysis, as a management platform, the management organization of the mega infrastructure construction must be equipped with an adaptation mechanism. As such, the platform can provide the basic conditions and the requisite environment for the subject group to make an adaptive selection.

The original meaning of mechanism is the construction and operating principles of machinery. If the machinery is perceived as a system, its construction and operating principles can be deemed as the structure and procedure of the system. Consequently, a mechanism can be regarded as a constituent element, that is, the interrelation and the operating procedure of a system or organization.

In this case, how can the organizational platform of mega infrastructure construction management establish a basic adaptation mechanism?

The organizational platform devises the adaptation mechanism in accordance with four major factors, namely, problems (tasks), subjects, resources, and the environment.

1. Problems (tasks). There are many types of management problems in mega infrastructure construction, and these problems span numerous fields and hierarchies. Among these problems are those that are considered big problems and those that are considered difficult problems. The subject's behavior of adaptive selection must be oriented toward these problems (tasks), and it is the nature and the features of these problems (tasks) to which the subject should adapt his thinking and, moreover, his adaptation objectives.
2. Subjects. Different management problems (tasks) require diverse abilities of the subject (Wiendahl and Scholtissek 1994; Baccarini 1996; Vidal et al. 2010; Bosch et al. 2011). For example, a difficult problem requires richer experiences and greater knowledge on the part of the subject, whereas a big problem demands the subject to possess powers or authority of office that match the problem. That is, the subject should have the power to make decisions regarding problems and propose solutions in accordance with relevant laws and regulations. This tends to be more important than the subject's knowledge and experience, as it directly relates to the legitimacy of the management program for mega infrastructure construction. Furthermore, the complexity of the problem (task) requires that the subject group possesses the adaptive self-learning capability to reach consensus. All of these require that the management organization of mega infrastructure construction be made up of subjects who can adapt to the problems (tasks). Moreover, the absence or arrogation of the subject's powers or authority of office can, under no circumstances, occur.
3. Resources. Platform resources suggest that the core subject offers conditions for the subject's adaptive selection by selecting the subject and designing the structure of the platform. It is emphasized that the platform must establish an operating mechanism that evolves from the individual subject's dispersive capacity to the subject group's overall capacity, which is the most critical resource function for management organization.
4. Environment. This refers to the operating environment within the management organization (Brockmann and Girmscheid 2008; Li et al. 2009; Bosch et al. 2011; Nguyen et al. 2015) and a coordination mechanism. For instance, specific methods regarding the association and cooperation among subjects selected in line with the features of problems (tasks) are as follows:

    1. An agreement contract specifically clarifies that each subject's powers and responsibilities be clearly defined and explicated by legal rules such that the subject's behaviors can be restricted within the laws and regulations, and thus, the legal rules become the rules for behavior by which the subject must abide.
    2. A relational contract focuses more on the cultural link among behavioral habits of the subjects based on a general contract. Moreover, it maintains the correlation and settles conflicts among subjects based on relations that extend

beyond the agreement contract. The major manifestation of the relational contract is that in the face of special circumstances, all concerned parties adopt a flexible disposal manner they understand and accept to create a strategic cooperative alliance featuring mutual trust for the sake of their long-term cooperation and common interests. The relational contract incorporates a partnership mode, a dynamic alliance, and a strategic cooperative alliance. Both a formal agreement contract and an informal relational contract are included within the management organization of mega infrastructure construction such that they complement each other and produce positive results.
3. An organizational contract, as a problem (task)-oriented teamwork approach, focuses on accomplishing tasks, rather than on assessing the interests of parties, and is primarily applied to cross-functional cooperation among multiple subjects during the management process. Given the circumstances, it is necessary to design the interfaces of the mechanism, the agreement, the culture, and the technology to establish a regular system for work and negotiations, develop common ideas, create a sense of mission, and build an information sharing platform.

In conclusion, the adaptation environment and coordination mechanism within the management organization is an agreement contract at the macro level, a relational contract at the mesoscopic level, and an organizational contract at the micro level.

Second, the management organizational platform can devise the adaptation mechanism in accordance with the four types of dynamic changes.

Since the four types of changes occur in practical activities of mega infrastructure construction management, the organizational platform should change accordingly and embody its adaptation function. Among these changes, the change in problems (tasks) is radical and thus assumes a leading role. Accordingly, all changes to the organizational platform are the result of changes in the problems (tasks) themselves, as demonstrated in the following:

1. The change regarding platform subjects occurs as a result of changes in the problems (tasks), as such changes place new demands on the subject's powers or authority of office, knowledge, and abilities. Hence, the platform should have a corresponding adaptation mechanism for subject change as well as other changes. Generally speaking, there will be more changes with respect to ordinary subjects in the group, whereas the core subject will usually remain stable.
2. The change in the platform structure is the result of changes in problems (tasks), as such changes may impact the interrelations and interactions of the platform subjects. Thus, the platform structure must be modified or reorganized to facilitate the emergence of new and indispensable abilities and functions that manifests due to alterations in the mode of construction management.
3. The change in the platform mechanism primarily refers to the change in workflow inside the platform. For example, the principal-agent relationship between the owner and the research unit is direct at the preliminary stage of the construction. However, it becomes an indirect trusting relationship as it changes to the designer and the contractors. In another example, in the beginning, the owner may establish business ties with the contractor and supplier yet change to a nominated subcontractor in later stages.

The flexibility embodied in this organization management platform gives full expression to the fundamental principles behind the platform's capability to control management complexity through the adaptation mechanism when managing problems (tasks) of complexity management. Flexibility is not only a fine quality of the management organization of mega infrastructure construction but also positively affects the subject group's adaptive self-learning behavior.

3. *Adaptation Evaluation of Management Programs*

In Sect. 5.2.4, we proposed the second type of adaptation—the adaptation of management programs. Even though it does not belong to the adaptation of subject behavior, the quality of the program, as the result of subject behavior of adaptive selection, will directly evaluate the quality of the subject's behavior of adaptive selection.

This gives rise to several questions. What constitutes quality with respect to the management program? Is the quality of the program the same as construction quality? Given the complexity of mega infrastructure construction, what quality evaluation method is used to assess the management program? This series of interrelated and sequential questions is, in fact, newly emerged scientific questions, and thus, we must draw relevant conclusions according to the principle of theoretical thinking and the argumentation of basic concepts and principles.

From the preliminarily established theory, it is inferred that the key to evaluating the quality of the management program for mega infrastructure construction is whether the management program can continue to play its role throughout the long life cycle of engineering and maintain its robustness in the face of possible changes in depth regarding the environmental scenario.

This theoretical perspective fully reveals the quality connotation of the management program when mega infrastructure construction management is characterized by complexity and when it plans to use the holistic coupling degree of the program function and the depth change of the environmental scenario to evaluate and measure the technical path of the program quality.

The change in the environmental scenario encompasses two types of scenario change:

1. The scenario change of the environment of the surrounding area before the forming of the mega infrastructure construction substantiality
2. The scenario change that emerged as the result of the synthetic system of the mega infrastructure construction environment after the formation of the mega infrastructure construction substantiality

This, however, requires identifying and forecasting the scenario change of mega infrastructure construction and managing the coupling degree between the management program and the change in the environmental scenario. This will be presented in Sect. 7.2 when discussing decisions regarding the deep uncertainty of mega infrastructure construction.

To sum up, adaptive selection is the code of conduct for the management subject of mega infrastructure construction and one of the subjects' behavioral capabilities in management activities. In management practice, adaptive selection should give full expression to the integration of theoretical thinking and engineering thinking. In conclusion, the primary connotation of adaptive selection is the enhancement of the adaptability of the management program through the adaptive selection of objectives and the designing of the adaptation mechanism for the management organizational platform.

6.3 Multi-Scale Management Principles

According to Sect. 5.2.3, it is determined that the concept of a multi-scale is universal in mega infrastructure construction management. The core idea is that among mega infrastructure construction management issues, the management element of a certain dimension has a certain ordering variation tendency. In addition, this variation tendency causes the management element to manifest different properties and features according to its dimensions, which then demands that we distinguish carefully and treat differently the different properties and features during practical activities and theoretical studies of mega infrastructure construction management. In this way, the degree of precision of the management element analysis and the level of mega infrastructure construction management will be improved greatly. For example, various problems should be taken into consideration during mega infrastructure construction decision-making, including time-space multi-scale issues such as the coordination between construction and the natural environment (Brockmann and Girmscheid 2008; Li et al. 2009; Bosch et al. 2011; Nguyen et al. 2015). During the specific decision-making process, subjects should not only consider those questions of different time-space scales but also integrate them and conduct a comprehensive evaluation that must engage different scales, for instance, whether the large scale must be narrowed or the small scale enlarged should be considered carefully. This suggests that regardless of whether it is at the practical level or the theoretical level, subjects should pay attention to and emphasize the analysis and management of multi-scale properties of mega infrastructure construction management activities.

6.3.1 Fundamental Connotations of Multi-Scale Management

Multi-scale management requires full attention to and careful distinction between the characteristic features that are caused by the multi-scale property of the management elements of the same dimension among mega infrastructure construction management activities. Corresponding management principles, processes, and methods should be designed and constructed in accordance with the diversities, thus revealing the complexities of these management activities.

First, multi-scale management is based on the following ideas: diversities are caused by various scales of management elements and have a profound impact on mega infrastructure construction management activity contents as well as relative management effects. In addition, it is these diversities that form the complexity of mega infrastructure construction management activities in a specific area (Li et al. 2009; Owens et al. 2012; Xia and Chan 2012). Therefore, it is improper to combine these diversities without consideration. For example, in Sect. 5.2.5, different time scales create huge differences among various types of functions, including constructive, generative, and emergent functions of mega infrastructure construction. Furthermore, diversities between types decide various function formation paths and evaluation methods, forming the concept of the function spectrum, which can reflect profoundly the complexity of mega infrastructure construction based on the traditional concept of construction multifunctions. If we do not distinguish the multi-scale phenomena in practical management activities and theoretical studies of mega infrastructure construction, it is possible to neglect the accurate structure of the mega infrastructure construction function spectrum, thus causing us to violate the thinking principles of mega infrastructure construction management ranging from systematicness to complexity.

Therefore, when managing multi-scales in mega infrastructure construction given its internal logics of multi-scale connotations, several aspects should be considered.

6.3.2 Multi-Scale Management: Multi-Scale Segmentation and Feature Extraction

1. *Segmenting Scales*

Even though multi-scaling is, to some degree, a universal phenomenon, it is unnecessary to segment and multi-scale management elements at any time or in any process when addressing questions. Whether it is necessary depends on the following two factors:

1. It depends on whether the various scales of management elements have a profound impact on the analysis and resolution of management problems. If these element's features at various scales have obvious effects on management issues, the dimension of this element should be segmented into scales. Furthermore, with the aims of easier description and distinction, different features should be added correspondingly.
2. It depends on the requirements for the precision degree of analysis and the resolution to management problems. In most cases, it is necessary to analyze carefully the effects of management elements on problems when analyzing complicated management problems, which requires an emphasis on the function of multi-scaling. However, if a precise analysis is not required, it is not necessary to segment the management element at corresponding scales.

2. *Conducting the Scale Segmentation of Elements*

If the scale segmentation of a certain management element is necessary, one must determine how to accomplish this. A multi-scale segmentation on the same dimension is similar to the division of several intervals on a straight line. However, multi-scale segmentation is much more complex than interval division. Most importantly, scales do not have interval straightforward measuring features such as lengths. Rather, in most cases, they just manifest qualitative or intuitive descriptions. For example, for time dimensions, short, middle, and long term can be used as scales, whereas for space dimensions, small, middle, and large range can be used as scales. Similarly, for uncertainty, shallow, moderate, and deep degree can be used as scales; for supplier locations, the centralized and the distributed ones can be used as scales, and abstraction, structuralism, semi-structuralism, and non-structuralism can be used as scales for issues. In conclusion, specific physical, constructional, or management connotations constitute the scale segmentation, and because scale segmentations are usually indistinct, they do not have obvious quantities or geometrical characteristics such as interval division. Generally speaking, scale segmentations are recognized as the boundary divisions of element features that subjects can distinguish intuitively.

3. *Extracting Features of Management Elements at Various Scales*

This question has been almost clarified during the multi-scale division and design. Initially, this is because of our discovery regarding the important features of management elements that are revealed at various scales on the same dimension and our recognition that features of different scales have significant influence on management problems, which compelled us to propose the concept of multi-scale. Thus, it is evident that the influence of management element features at different scales on management issues usually becomes the orientation that guides people to conduct multi-scale segmentation. This illustrates that multi-scale segmentation is a highly purposive and practical managing behavior and that the important justification is that under the premise of extracting different scale features of management elements, an association analysis of management problems and different features should be conducted given that features exhibiting the same type of association should belong to the same scale basically. For instance, considering the single scale, people usually focus on the direct physical function of mega infrastructure construction, namely, constructive function. With respect to the short- or middle-term scale, people usually distinguish between constructive function and generative function. If the long-term scale is added, people will consider an emergent function in view of the behavioral characteristics of the mega infrastructure construction-environment complex system, thus revealing the unique complexity of the mega infrastructure construction function spectrum.

4. *Making Full Use of the Function of Multi-scale Features*

The practical significance of extracting features of management elements at different scales is to fully reveal the influence of various features on management problems and then precisely analyze and resolve complex problems. These are the most fundamental functions of multi-scale management.

The tasks to be completed here are based on the accurate extraction of element features at various scales, specifically, to describe or measure scale features and analyze and establish association functions and influences between various features and management issues. If these tasks are not expertly completed, it will be difficult to demonstrate the practical significance of multi-scale management.

Therefore, subjects should extract specific features not only from various scales and construction management connotations contained in the features according to theoretical thoughts but also from the perspective of construction ideas. Moreover, they should consider the associations between various features and management elements to clarify the actual influences of these features on management issues.

For example, though the multi-scale based on the time dimension is a universal phenomenon, we cannot simply divide the time dimension into the short, middle, and long term and then assume that it shows and completes multi-scale management because the real significance of this segmentation is to seek the characteristics of various scales based on the scientific connotations of the management elements. For instance, the characterization of the mega infrastructure construction function, a management element at different time scales, is the formation of different paths that are composed of important differences among them. The features of the different formation paths of the functions should be embedded into the mega infrastructure construction function design management, and accordingly, the actual function spectrum design activity of a certain mega infrastructure construction can be conducted according to the different formation paths. Among these, the constructive functions and generative functions usually adopt traditional construction planning and design as well as social economic comprehensive analysis methods. However, the adoption of traditional methods cannot discover or predict emergent functions. Thus, new methods are needed to discover and predict the large time scale scenario evolution of the mega infrastructure construction environment. Accordingly, the large time scale emergent function of mega infrastructure construction is formed based on the new methods and the large time scale scenario.

It is specifically noted that despite the same dimension, such as the division of the time dimension into the short term, middle term, and long term, many aspects must still be considered during the extraction of the various features, such as what types of issues are studied, what types of associations exist between issues and elements, and whether these associations can distinguish among the more delicate element features. There are no absolute answers to these questions.

For example, regarding the mega infrastructure construction management environment, the influence of different time scales with the same time dimension is reflected by the degree of severity of environmental uncertainty. Thus, it is necessary to divide uncertainty into three scales, namely, the shallow degree, the moderate degree, and the deep degree, according to the short term, the middle term, and the long term, which is quite different from the concept of the function spectrum, which is based on various time scales. As for management elements of different dimensions, characterizations, and description methods that are extracted according to multi-scales, their effects on management issues and all management connotations presented by these issues must be analyzed and clarified separately and in combination with the specific construction management issues.

6.3.3 Multi-Scale Management: Integration from Multi-Scales to Dimensions

The multi-scale segmentation of management elements of the same dimension can be regarded as one of the subject's complex degradation methods of theoretical thinking, to some extent. Nonetheless, mega infrastructure construction management practical activities demand that we not only segment the scales of virtual construction but also integrate scales of actual construction into dimensions. In other words, it requires us to integrate management elements from multi-scales to their original dimensions and to then study management issues at their original dimension. This is one of the most important steps for multi-scale management in practical operations because without it, even though we have already refined the complexity of management elements at the same dimension through the concept of multi-scales, this step denotes degraded complexity. Therefore, we should conduct the integration at management element dimensions and then, based on the results, examine the level of complexity.

In conclusion, multi-scale management consists primarily of two stages. The first stage is to segment dimensions on scales based on reductionist ideas and to analyze associations with management elements and influences on management problems by extracting various scale features. The second stage is to conduct the integration of a multi-scale analysis of dimension levels based on ideas of holism and to then form the perception of management issues given the meaning of the dimensions. Multi-scale management with respect to the meaning of system theory has been formed under the combination of scale segmentation of reductionism with dimension integration of holism.

With respect to the specific technologies and methods of multi-scale management, in the stage of multi-scale segmentation, the corresponding construction management activities and backgrounds are relatively centralized and simple due to the scale segmentation as well as the features, properties, effects, and functions of the scales. This suggests that there should be increased focus on the complexity of certain aspects of management elements. From the perspective of the prescriptability and usability of corresponding construction management technologies and methods, systematic analyzing technologies and methods are usually adopted.

Regarding the stage of dimension integration, the principles of holism are reflected, and thus, critical path methods of management objectives (functions) and all types of comprehensive evaluation technologies are adopted.

The fundamental principle of comprehensive evaluation technologies is to build a comprehensive utility function (index) that characterizes the management elements of the entire set of dimensions, which includes subjects' value orientations as well as features, functions, and influences relevant to all scales. Next, by combining specific methods, the perceptions that subjects have, which are based on a combination of objective properties and subjective values, will be obtained.

There are many typical comprehensive evaluation methods, among which are the following:

1. Methods orientated with expert qualitative comprehensive evaluations are usually used to solve non-structural issues, such as macro or strategic management issues of mega infrastructure construction, because it is difficult to describe such methods quantitatively and create structured models (Kumar and Bansal 2012; Meng and Chen 2016).
2. Factor analysis, principal component analysis, clustering analysis, and other methods are used to conduct a comprehensive evaluation of multi-scale features and effects (El-Mashaleh et al. 2010; Ozbek et al. 2010).
3. The scoring method, relational matrix analysis, and analytical hierarchy process of system analysis are used to conduct a comprehensive evaluation (Shaphira and Goldenberg 2005; Lai et al. 2008; Wang et al. 2009; Bobylev 2011).
4. Fuzzy recognition, fuzzy comprehensive evaluation, and other methods are used to conduct a comprehensive evaluation (Opricovic and Tzeng 2004; Mahdavi et al. 2008; Park et al. 2009; Park et al. 2010; Mohammad et al. 2012; Heravi and Esmaeeli 2014).
5. Computer simulation is used to conduct process analyses and comprehensive evaluations.
6. Objectivity and subjectivity of the multi-scale features are combined through man-machine conversation, forming an interactive, multi-objective, comprehensive evaluation method.
7. Two or more comprehensive evaluation methods are integrated and improved, and the more comprehensive evaluation methods are integrated, such as in fuzzy clustering analysis, which combines the fuzzy evaluation method with the clustering evaluation method, and the fuzzy artificial neural network method, which combines the fuzzy evaluation method with the artificial intelligence method.
8. Additionally, comprehensive evaluation methods based on method set combination and evaluation support systems based on computers are used.

These comprehensive evaluation methods have been formed and applied successfully in various fields over the past several years. Their fundamental ideas can provide valuable information as we seek to manage and solve many comprehensive multi-scale issues. However, as the system integration and its evaluations are usually complex and difficult, we cannot directly apply these comprehensive evaluation methods, which are successful in other fields, to mega infrastructure construction multi-scale management. Furthermore, what is more important than choosing and introducing suitable and mature comprehensive evaluation methods is the integration of theoretical and constructional ideas in the practical activities of construction management.

In conclusion, *multi-scale management is dependent on the multi-dimensional analysis of management elements in mega infrastructure construction activities to conduct the multi-scale segmentation of management elements at the same dimension and analyze the influence of different scale features on management issues for the integration of all dimensions based on multi-scale analysis. This constitutes the complete scientific connotations of multi-scale management principles.*

6.4 Generative Principles of the Iterative Pattern

As previously noted, choice based on adaptive criteria is the most universal and most common behavior for subjects engaged in mega infrastructure construction management activities. Theoretically, however, people should be familiar with the general rules regarding subjects' selection behavior on the practical level, such as the rule that it is necessary to clarify the main purpose-related orientation of the subjects' selection behaviors, the basic procedures of selection behavior, and the features of the technical route during the process of choice, as this constitutes the basic code of conduct for management subjects during mega infrastructure construction management activities. If we are clearer about these questions, we could have a more thorough understanding of the general rules regarding subjects' behaviors during mega infrastructure construction management activities.

6.4.1 Iteration of Subjects' Behavior During the Process of Choice

From the perspective of construction ideas, the fundamental goal of subject behavior with respect to choice is to make choices that will allow them to first devise a program that will contribute to solving management issues and to then implement that program.

When considering a relatively simple construction management issue, people usually make the objectives clear, conduct a strict analysis, establish models, and select solutions from several feasible programs using optimal techniques because the management goals are usually explicit and the issues are highly structured. *This type of program generation mode is called optimal generative principles.*

However, with respect to complex problems among mega infrastructure construction management, this type of optimal generative mode may confront huge barriers due to the complexity of the issues for the following reasons:

1. The management objectives of complex issues usually involve multi-level, multidimensional, and multi-scale features.
2. It is difficult to use structuralized models to describe complex issues thoroughly.
3. It remains challenging to solve models due to their complexity, even though we create structuralized models.

In this way, although the subjects' selection behaviors focus primarily on the proposal and confirmation of the programs for management issues among mega infrastructure construction management activities, subjective and objective factors still impact the results such that it is difficult for subjects to generate programs through optimal generative principles.

At this time, subjects can only confront the complexity of issues through self-adaption behaviors according to the adaptive criteria. Accordingly, subjects should improve their knowledge and abilities through self-learning. As for issues, subjects should degrade the complexity of the problem, compact and synthesize management objectives, and conduct a multi-scale segmentation of the features of the issues. The question is: how can all of this be accomplished? The practical procedure of this operation will be analyzed below.

1. *Subject Iteration of the First Level*

As an individual among management subjects, the individual should engage in a self-learning activity to improve the ability of selection. Learning is a complicated process for humans, especially learning that aims to improve cognition regarding the complexity of mega infrastructure construction management and the ability to manage it, which is based on creative thinking and belongs to the category of intelligent behaviors. It includes not only comprehension, understanding, and knowledge accumulation but also the processes of saltation, leap, and insight. According to the Gestalt theory of cognitive learning, an organized unity based ultimately on the subject's cognition, namely, Gestalt, rather than on the simple formation of the combination of stimulations and reactions should be formed (Kurt Koffka 1935). Regardless of how, the subject's self-learning should gradually grasp the essence of unresolved issues and apply learning outcomes to the relevant situations. This is a self-iteration process of the subject's cognitive thinking. During such a process of continuous iteration, the subject's information and knowledge are further enriched, and his/her recognition of issues and relative solutions becomes increasingly complete and profound. The duration of this iteration process and its effects vary from person to person because the problems are of various different levels and the processes follow different tracks. Nonetheless, no one succeeds on the first attempt due to the rules of human learning and cognition.

We call this iteration behavior, which impacts individual subjects, *iterative behavior of the first level*, as it is the most fundamental iterative behavior during the process of selecting mega infrastructure construction management programs.

2. *Subject Iteration of the Second Level*

Mega infrastructure construction management issues involve various fields, including politics, society, economics, technology, and cultures, and as such, it is not possible for one individual or even a few subjects to possess all knowledge and resources required by the management activities. Therefore, the process of selecting the mega infrastructure construction management programs requires not only that management subject individuals attain a relatively high level of recognition, analysis, and comprehension regarding the issues but also that a subject group composed of individuals from different fields works together to resolve problems. Moreover, different authorities and expert knowledge are needed to solve the various problems, factors that determine the constitution of the mega infrastructure construction management subject group and factors that, in general, should not be "fixed" or modified. Instead, based on the properties of the issue, subjects should constantly be selected such that the subject group's constitution conducts suitable shifts under the leadership of core subjects and thus forms a new subject platform. From the perspective of the selection process, it is a continuous iteration for both the management subject groups and the management platforms that is consistent with the concepts of reorganization and reconstitution. Through this iteration, management platforms adaptively generate authorities and abilities that are linked to the identified problems. This is a type of iteration behavior that is conducted among subject groups during the process of selecting mega infrastructure construction management programs, and it is called *iteration behavior of the second level*, which is on the same level as the management platform and tantamount to management organization during the selection of mega infrastructure construction management programs.

The iteration of the management platform aims to ensure that the organization completes and implements the management programs and that the programs are of high quality. Furthermore, such iteration requires the subject group to adopt an effective method that is founded upon the platform's dynamic iteration when selecting management programs.

3. *Subject Iteration of the Third Level*

With respect to a specific management issue, the subject group forms one or several original programs in the beginning, according to the platform working mechanism. Then, through multidimensional analysis and evaluation and according to the conclusions derived from the analysis and evaluation, the group may modify and complete the initial programs, which constitute an iteration of the vertical process, or the group may compare, delete, and reorganize the original programs, which is an iteration of the lateral process. In practical management activities, regardless of vertical iterations or lateral iterations, numerous iterations must be conducted until the process is completed for the following reasons:

1. The comparison between many mega infrastructure construction management programs is a dynamic comprehensive evaluation of a complex systemic function of management programs. It must not only change the individual evaluation into multiple evaluations for program functions but also be based on the comprehensive evaluation according to the meaning of the program function spectrum. Especially during the evaluation process, with the deepening of the subjects' cognitions and changes in values, it is essential that program iterations be conducted and repeated.
2. During the process of comparing programs, relative data, relevant information, expert knowledge, and expert experience are important. However, only during the actual operation can relative data and information become abundant and complete. Expert knowledge and experience can only be released after several comparisons are conducted.
3. Overall, the comparison between programs requires subject consensus during the selection process. The consensus marks the gradual concentration and convergence of individuals' recognition of the complexity of the issues. This process

first depends on the degree of the issue's complexity, which means that the more complex the issue is, the more difficult the convergence will be. Furthermore, more complex issues require more comparisons and iterations. The process is also dependent on the evolution of values that are formed through subjects' self-learning experiences. For instance, if subjects raise their awareness of environmental protection, they may reject original programs with low environmental protection qualities and instead devise programs with higher environmental protection qualities. This suggests that the original consensus becomes non-consensus. Such circuitous and duplicative iteration patterns usually occur during the practice of mega infrastructure construction management.

Thus, it is evidenced that on the level of practical operation, the selection process of mega infrastructure construction management programs consists of vertical or lateral iterations of programs. During this process, the comprehensive evaluation of subjects and the cognitive advancement or the forming of program consensus for subject groups reflect a universal model of continuous comparison, gradual accuracy, and ultimate determination. This is an iterative behavior that is played out during the forming of subject group consensus as part of the selection process of mega infrastructure construction management programs. Thus, we term it *iteration behavior of the third level*, and it is the iteration behavior that is at the highest level during the selection process.

To sum up, on the operational level, the selection behavior of mega infrastructure construction management programs illustrates a three-level comprehensive iteration model with mutual feedback that is composed of the "individual subject's self-learning iteration-subject group platform and iteration-subject group consensus-forming iteration." The specific process is a process of continuous iterations, which means that subjects continue to conduct vertical or lateral comparisons, adjustments, and revisions of programs at a certain stage, overturn original programs, redesign new programs, and employ successive iteration program sequencing to develop the ultimate program.

From the perspective of theoretical ideas, if there exists an optimal program for a certain mega infrastructure construction management issue, subjects gradually approach this optimal program through continuous comparison and correction during the process of program selection. *It is called the generative principles of an iterative pattern of mega infrastructure construction management programs, and to describe its overall operating procedure and process, it is summarized as comparison, iteration, and approximation.*

One can conclude from the perspective of technical routes when suggesting programs that the generative principles of an optimized pattern immediately integrate the issue of complexity into the selection behavior of programs. To perform this in practice, there are two important points to remember, namely, issues should not be too complex and subjects should have strong abilities. However, in mega infrastructure construction management activities, these two criteria are difficult to satisfy. However, the generative principles of an iterative pattern degrade the complexity of issues at various stages of the program's generation, which means not only that the

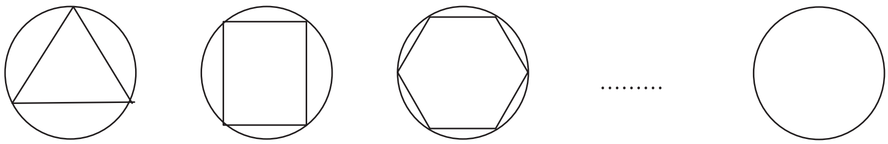

Fig. 6.4 Iterative schematic diagram of calculating the circumference of a circle

complexity that subjects confront in each stage becomes a part of the overall complexity but also that the subjects adopt program sequences formed after the adaptive iterations to achieve the ultimate program objective. This practical operating behavior reflects both the subjects' complexity degradation principles and their adaptive selection principles.

These types of generative principles of an iterative pattern, namely, the optimal program principles integrated through comparing, iterating, and approaching a certain complex issue, are also applied widely in other fields. For example, in the field of mathematics, determining the circumference of a circle is a complex problem. Before people invented calculus, i.e., in a period when man's cognition levels were relatively low, the method of calculating the circumference of a circle based on inscribed regular triangles, regular quadrangles, regular hexagons, regular octagons, etc. was usually adopted. By adding the number of sides of the regular polygons, the iterative sequence of the circle's inscribed regular polygon perimeter is created, and this can then be used to calculate accurately the circumference of the circle. It is undeniable that there exists an error when adopting the method of using regular polygons inscribed within circles to determine the circumference of a circle. Though this type of error exists in any finite iteration, we can reduce errors by increasing the number of iterations. In the calculation process, the number of iterations is dependent on the accuracy that we require, which is similar to the situation of knowing when to stop during the process of complexity degradation (Fig. 6.4).

6.4.2 Iteration of Technology Roadmap During the Selection Process

As previously mentioned, the iterative generative principles of mega infrastructure construction management programs usually manifest subjects' contrastive behaviors at the operational level. The technology that is adopted, by contrast, is comprehensive evaluation, and its key technology roadmap involves the target composition as well as a qualitative and quantitative composition. Even though the core technologies of both fields are widely used in management practice and some typical methods have been introduced in Sect. 6.3.3, the technologies still manifest the obvious iteration in real practice. Thus, it is meaningful to emphasize and explain them before we apply them. Specific explanations are as follows:

1. *Iteration of Comprehensive Purpose Contrast*

Regardless of whether it is the vertical or the lateral iteration of management programs, the comparison should be conducted at the same depth with united values under the same circumstances, which requires subjects to put forward comprehensive targets of comprehensive evaluation technologies (Li et al. 2009; Xia and Chan 2012; Owens et al. 2012).

For example, during the comparison of the Chinese mega bridge engineering bidding plans, 35 indexes are selected at the beginning. To ensure that the evaluation indexes are more representative and varied, management subjects further condense these indexes, rank them in order of importance, and conduct a cluster analysis using the set occurrence iterative method. Finally, 15 evaluation indexes that are not only extensively representative but also highlight the main factors of the evaluation targets are then condensed.

Thus, it is evidenced that when dealing with targets, subjects must sift or merge the targets during each stage and make qualitative or quantitative judgments of the associations among the targets during the process of comprehensive evaluation. However, when entering the next stage, subjects must conduct a similar iteration based on the evaluation at the previous stage. This is the iterative connotation reflected through the subjects' comprehensive technology roadmap of the target.

2. *Iteration of Qualitative and Quantitative Comprehensive Integrations*

Because of the complexity of mega infrastructure construction management programs, subjects usually form thoughts, assumptions, and concepts of programs as a whole and combine the subject group's intelligence before forming subjective judgments that give priority to language and word descriptions based on existing scientific theories, experience, and knowledge. This is known as the qualitative method in program generation, which includes the subjects' overall analysis and design of program goals and functions, a relevance analysis of issues and circumstances, a technology roadmap design for forming programs, and the requisite comprehensive evaluation indexes and standards for those programs. Observations, narrations, analyses of cases and archives, and field surveys are all common qualitative methods (Turner and Cochrane 1993; Bosch et al. 2011; Lebcir and Choudrie 2011; Lessard et al. 2014). The conclusions yielded by qualitative methods are usually experiential assumptions, plans, preliminary program ideas, and technology roadmap descriptions (Maylor et al. 2008; Geraldi et al. 2011).

However, when advancing a mega infrastructure construction management program, accurate quantitative characterizations of relations among the program elements are necessary because ordinary languages and word descriptions are usually too nonspecific for construction works. The quantitative method is necessary for program generation, as it applies logical reasoning, models, data analysis, simulation experience, and other methods to achieve accurate calculations and strict proof of issues and relationships within the programs. Quantitative methods are usually based on qualitative methods and relevant conclusions, and thus, they apply precise logical reasoning and mathematical deduction to identify accurate solutions and perform relevant demonstrations. For example, precise comparisons among the different program functions, parameter determinations in the programs, etc. use quantitative methods (Frizelle and Gregory 2000; Mihm et al. 2003; Vidal et al. 2011b; Owens et al. 2012). Data collection and analysis, mathematical modeling and model solution, and computer simulation and emulation are all typical qualitative methods (Xia and Lee 2004; Remington and Pollack 2007; Vidal and Marle 2008; Shafiei and Jenab 2012; Gransberg et al. 2013).

With respect to mega infrastructure construction management programs, the designs of structural parts often adopt quantitative methods, whereas the descriptions of non-structural parts adopt qualitative methods. Accordingly, the overall program selection of issues not only applies qualitative and quantitative methods but also combines the two methods.

Therefore, during the selection process of mega infrastructure construction programs, we must determine how to manage the relationships between qualitative and quantitative methods.

First, when people initially begin to realize and analyze the complexity of issues, they rely on descriptions to illustrate external performance characterizations, use language to describe speculative contents, and use experience and feelings to establish conceptual frameworks. Such a process not only conforms with those cognitive features that humans are skilled at conducting from the top down and from individuality to universality but also aligns with the fact that it is difficult to conduct accurate quantitative descriptions of nonstructural parts integrated in complex issues. During this stage, human induction, understanding, knowledge, and experience play important roles and lay the foundation to adopt standard procedures and accurate means for the strict, precise analysis of issue. The qualitative stage depends primarily on the subjects' continuous deepening of recognition with respect to issues and programs. It is through iteration that this increased depth gradually occurs.

Second, many mega infrastructure construction programs and core technologies have a direct and profound influence on constructions (Baccarini 1996; Mihm et al. 2003; Harty et al. 2007; Bosch et al. 2011; Xia and Chan 2012; Hu et al. 2014). Confronted with these types of issues, we should not only develop qualitative descriptions of these problems but also conduct a clear and accurate analysis of them. Only in this way can errors possibly be avoided and the quality of the entire construction management program be guaranteed. Quantitative demonstrations, especially the adoption of several quantitative methods, are vital to perfect quantitative recognition and guarantee the scientific nature of construction mega programs. Especially with respect to complex issues among mega infrastructure constructions that have strong integrity and close relations with external uncertain circumstances, it is necessary for subjects to experience the process of a gradual deepening of recognition based on acknowledgment and understanding during the preliminary stage via data collection and analysis, monitoring and simulation, selection of prediction methods and improvements, and modification of quantitative results. These activities are all completed during the process of continuous iteration.

Finally, resolutions to complex mega infrastructure construction issues require combinations of quality and quantity. Complex mega infrastructure construction issues generally have interdisciplinary, cross-disciplinary, and multi-level features.

Therefore, an empirical hypothesis regarding the study of issues can only be achieved by employing expert systems that consist of experts from different fields, subjects, and levels, rather than those from a specific field or a specific subject. The integration of group experience, knowledge, and intelligence and the development of group consensus are referred to as a qualitative comprehensive integration. When using quantitative methods, it is necessary to adopt integrations of multiple models, multiple calculation tools, and multiple quantitative measures according to the general purposes and principles. This is referred to as quantitative comprehensive integration.

Qualitative comprehensive integration and quantitative comprehensive integration apply informatization techniques and networking strategies to realize the integration of expert knowledge, intelligence, and experience. The quantitative comprehensive integration is completed by establishing a model base, i.e., a conceptual model, structural model, or mathematical model, a data base, a method base, and a rule base while also establishing a decision support platform centered on the knowledge base and information base as knowledge stock and intelligence support during the qualitative and quantitative comprehensive integration process. Thus, it can be concluded that selection programs of mega infrastructure construction complex issues require not only the combination of qualitative and quantitative methods but also the application of comprehensive integration methods from qualitative ones to quantitative ones.

It is evident that during the aforementioned process, several iterations should be conducted before the final completion within the interior of the qualitative and quantitative stages. Moreover, qualitative iterations and quantitative iterations mutually influence each other and then trigger mutually new iteration needs, forming qualitative and quantitative features of interactive iterations throughout the entire quantitative-qualitative combination process.

Although many technologies and methods are used during the selection process of mega infrastructure construction management programs, the most widely used are the qualitative and quantitative combinations of major technologies and methods. Regardless of the interior of qualitative comprehensive integrations, the interior of quantitative integrations, or the mutual transformations between the two, they all exhibit a process of continuous iteration. It is these types of multi-level iteration methods that compensate for their own disadvantages, form a new stronger ability to make decisions and selections, and reveal the basic generative principles of an iterative pattern that is demonstrated during the process of program selection at the operational level when they play the role of qualitative and quantitative methods.

6.5 Hierarchical Principal-Agent Principles

The subject group of mega infrastructure construction management is a platform of multiple levels and complex structures, rather than an unordered subject collection. In practical management activities, the subject group functions as a management organization that abides by certain mechanisms and regulations. In most instances, the specific pattern and form of a mega infrastructure construction management organization represent variety and diversity according to its own features, construction circumstances, construction subjects, and, especially, core subject's cultural values and management habits. However, due to the gradual separation of mega infrastructure construction ownership and decision-making rights, management rights, construction rights, and operation rights, a hierarchical principal-agent relationship is generated among construction subjects. In addition to the systematic complexity of multiple levels and multiple scales, this relationship allows mega infrastructure construction organizational platforms to represent multi-subject coordination, right allocations, and other management complexities. Therefore, according to the basic principles of the hierarchical principal-agent relationships, it is not only beneficial to analyze the complicated relationships among several mega infrastructure construction subjects but also advantageous to design and optimize mega infrastructure construction management organization patterns.

The hierarchical principal-agent principles of mega infrastructure construction management reflect the complex dynamic relationships and the motivations of the management organization mechanism within the management subject groups.

6.5.1 Mega Infrastructure Construction Hierarchical Principal-Agent Relationships: Overview

Mega infrastructure construction is an infrastructure project that meets the needs of social citizens (Baccarini 1996; Williams 1999; Thomas and Mengel 2008; Vidal and Marle 2008; Bosch-Rekveldt et al. 2011; Browning 2014) and has relatively strong features related to public goods. Public finance is the primary investor in mega infrastructure construction. Therefore, from the perspective of property rights, social citizens own the greatest portion of the mega infrastructure construction. However, for many reasons, it is impossible for the public to participate directly in the decision-making and management of mega infrastructure construction affairs (Baccarini 1996; Williams 1999; Geraldi and Adlbrecht 2007; Vidal and Marle 2008; Larson and Gray 2013). The public, as an initial client, can only authorize a certain level of government to participate in the mega infrastructure construction decision-making and management with respect to political, legal, and democratic aspects. This, to a large extent, generates the separation between mega infrastructure construction ownership and decision-making authority.

In the beginning, as the major decision-making subject of the mega infrastructure construction, and after receiving the principal of the public, the government usually assign some or all management functions to government departments or social professional institutions according to relative legislations and market rules, which generate a further separation between the decision-making rights and management rights of the mega infrastructure construction.

Based on the guarantee of functional departments and professional institutions' control rights over construction management, construction establishment and management assignments are further refined. Then, through bidding and other processes (Jap and Naik 2008; Cheng et al. 2010; Chua and Li 2009; Harper et al. 2014; Mahdavi and Hastak 2014; Ballesteros et al. 2015), specific construction establishment assignments are delegated to professional design organizations, construction organizations, and supervision organizations, thus generating the separation of management rights and construction rights.

Therefore, all subjects from the mega infrastructure construction management subject group experience the principal-agent process of property rights, decision-making rights, management rights, and construction rights several times and at multiple levels. They are then accepted into the construction organizational platform and become fundamental subject elements in the mega infrastructure construction management organization(system).However,theprincipal-agentchainofthepublic-government-government departments-construction managers-construction organizations forms a hierarchical principal-agent relationship chain of the mega infrastructure construction management organization as a whole. This is called the *mega infrastructure construction hierarchical principal-agent relationship for short or the mega infrastructure construction hierarchical principal-agent relationship of a government pattern*, as shown in Fig. 6.5.

Because of the differences among the principal subjects and the agent subjects of the mega infrastructure construction management subject group, stable and benefit-balanced relationships between the principal and the agent and between the agent

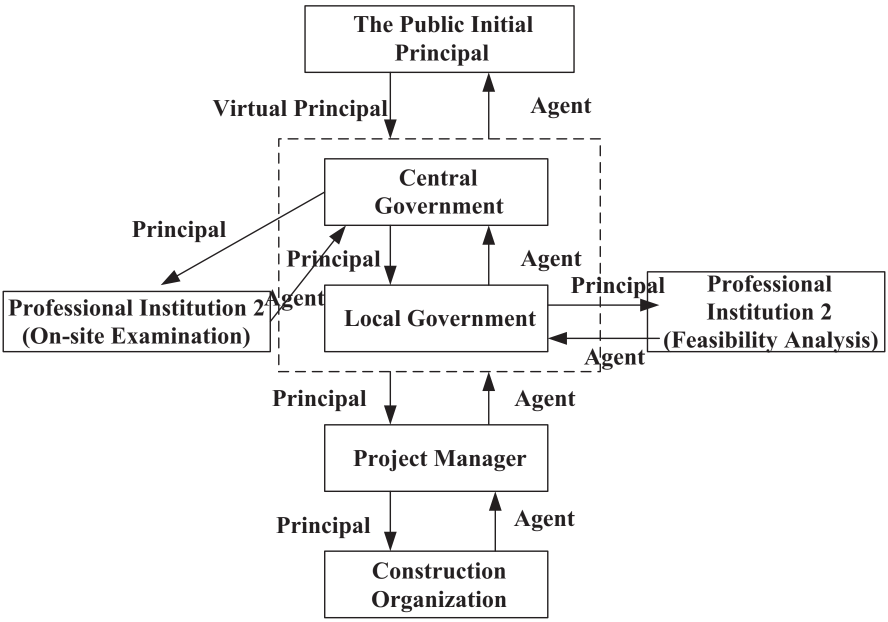

Fig. 6.5 Figure of mega infrastructure construction hierarchical principal-agent relationship

and the principal could only be realized through certain mechanisms. In practical mega infrastructure construction management activities, this mechanism must reflect not only the administrative function of the government as a major subject but also the resource-allocating function of the market economy. This then forms the organization contrast relationship of the administration-market coordination, which has many forms and is binding for interested parties. *It is this type of contrast relationship that guarantees the stable structure and the overall ability of the mega infrastructure construction management organization. This overall contrast relationship system and its stable dynamics constitute mega infrastructure construction principal-agent principles.*

According to Fig. 6.5, in the mega infrastructure construction iterative principal-agent chain, the following types of principal-agent relationships exist:

The first type is the principal-agent relationship between the public and the government.

As taxpayers, social citizens pay taxes to the nation and authorize the government to implement infrastructure construction projects according to legislation to realize and satisfy citizens' common interests. This is the most representative principal-agent relationship from among the government patterns in the mega infrastructure constructions, and as such, it is different from the standard principal-agent relationship with respect to institutional economics. Furthermore, this relationship can be regarded as a principal-agent relationship in the meaning of politics and law. In fact, social citizens who have close interest relations with a certain project constitute a small part of society, while the government's public power of administration is relatively strong. Thereby, it is possible for the phenomenon of weak principal and strong agent to appear, causing problems from different fields to arise. The most common problem regards a situation where the government lacks supervision. In such an event, it is possible that the government exhibits power alienation. For instance, as initial principals, the public should be responsible for the supervision and evaluation of the agent, i.e., the government, to ensure that the results of the agent's behavior are in accordance with the interests and goals of the principals. However, because there is no material contract or agreement between the public and the government in the economic sense, contract terms cannot be used to encourage or restrict the government. Furthermore, it is easy for the government to monopolize and control a great deal of mega infrastructure construction information, and given that the cost of public supervision is relatively high, the result is that some of the government's behaviors, more specifically, the behaviors of certain officials, may deviate from the purposes of the entrusting social citizens and may be combined with their own rent-seeking behaviors, which could damage the interests of the initial principals.

The second type is the principal-agent relationship among government agencies of different levels.

There are several levels in government. If the scale and the influence of the mega infrastructure construction project are substantial, it is more likely that a high-level government agency will be involved in the project. Because a wider field is involved in this construction project, the project requires more capital investment, the influence on the economic society of the nation and the local community is more profound, and the decision-making subjects, i.e., primarily the government, have more rights and greater ability to integrate resources. Accordingly, it is generally only high-level government agencies that meet these types of requirements. In addition, regardless of the type of mega infrastructure construction being considered, its material boundary is always limited, as it is in the jurisdictional area of one or more local governments. Therefore, in the practical process of construction establishment and management, in many cases, the higher-level governments must authorize the lower-level governments that belong to the construction area to manage and complete issues related to construction establishment and management, thus forming a principal-agent relationship between the higher level and lower level of government. This includes certain functional departments of the higher and lower levels of government. Especially when the construction involves specific public products of the local community and supplies items of public service, it is more reasonable that the high levels of government authorize the lower levels of government to oversee certain aspects of the construction. For example, a higher level of government authorizes a lower level of government to organize professional departments for the purpose of conducting a pre-feasibility analysis of the construction establishment according to the local social, economic, and environmental factors. The higher level of government also determines whether to approve the project based on the analysis reports and project proposals submitted by the lower level of government. It is also a nonstandard principal-agent relationship from the administrative perspective. In such a relationship, the lower level of government possesses obvious information advantages when executing procedure as an agent. In this sense, it is possible for the local government to use information asymmetry to select programs that are beneficial to themselves and to conduct invisible induction and exert influence on the higher-level government body, thereby causing the higher-level government agency to make errors when making decisions.

The third type is the principal-agent relationship between the government and professional institutions.

The government does not possess the professional technical capabilities that are required by mega infrastructure construction management. Therefore, it must authorize professional institutions to conduct analyses and make determinations regarding important decisions and technology issues with respect to mega infrastructure construction. Because of the differences in the social statuses and characteristics of subjects on both sides, the principal-agent relationship is a standard contract relationship. Accordingly, professional institutions take full advantage of their skills and apply a variety of effective means to complete assignments authorized by the government. It is also possible for such professional institutions to make moral mistakes due to their information advantages and their positions as agents. For example, they may take credit for research achievements and intellectual properties or seize opportunities to seek illegitimate economic interests.

The fourth type is the principal-agent relationship between the government and project managers.

Project managers play a vital role in mega infrastructure construction management. Over the past several decades, mega infrastructure construction management methods have experienced a revolution from traditional infrastructure offices and engineering commands to a pattern of agent-construction systems. At present, some construction managements have already implemented agent-construction systems, though the traditional systems still comprise the vast majority of systems. Thus, two types of relationships exist in the principal-agent relationship between the government and project managers. One is an administrative principal-agent relationship between the government and project managers under the pattern of traditional construction management, which is similar to the second type, i.e., the principal-agent relationships between government agencies of different levels. However, when adopting the new management pattern of agent-construction, as a principal, government departments select professional project managers to take charge of and oversee the construction investment management and construction management assignments through bid invitations and bidding. In this situation, a standard principal-agent relationship, similar to that in economics, is established between government departments and project owners. Problems that may occur are similar to those that occur in the third type of relationship, i.e., the principal-agent relationship between the government and professional institutions.

The fifth type is the principal-agent relationship between project managers and construction companies.

To benefit the labor division in society and to improve the quality and benefits of the mega infrastructure construction project, construction managers usually use a form of bidding to select construction companies. Under the premise of guaranteeing mega infrastructure construction control rights, as a principal, construction managers authorize construction companies to complete specific construction establishment activities with limited resources and in a limited amount of time. Because of the heavy workload associated with a mega infrastructure construction project, the long construction period, the complex relationships, and the great challenges regarding on-site control, there is obvious information asymmetry and uncertainty with respect to contract implementation between project managers and construction companies. In certain cases, construction companies may harm construction owners and other project managers' interests as they seek to maximize their own interests by exploiting their information advantages and opportunistic behaviors. Thus, principal-agent relationships, in the strict meaning of economics, are formed between project managers and construction companies, and their problems are similar to the third type of relationship, i.e., the principal-agent relationships between the government and professional institutions.

6.5.2 Features of the Mega Infrastructure Construction Hierarchical Principal-Agent Relationship

Thus, it can be concluded that a multi-level hierarchical principal-agent chain is formed among the mega infrastructure construction subjects of multiple levels. In contrast, standard enterprise principal-agent issues are characterized, generally, by a single chain, namely, a single principal and a single agent. However, in mega infrastructure construction principal-agent relationships, if the operation principles are not sufficiently scientific, management organizational platforms will experience far greater efficiency loss, and the costs will be higher due to the increased number of levels and subjects as well as the increased complexity of the relationships. Therefore, it is necessary to conclude and extract the basic features of this multi-level hierarchical principal-agent relationship.

1. *Coordination of the Principal-Agent Relationship*

   Because of the many mega infrastructure construction assignments, the different participants have different goals and behaviors. The principal-agent relationships must not only fully perform participants' functions but also integrate participants' functions. For example, during the period of the project feasibility study, project managers of the Chinese Hong Kong-Zhuhai-Macao Bridge authorized various institutions to conduct more than ten studies regarding soil and water conservation, bridge trans-boundary management, port layout patterns, and the influence of bridge projects on the *Sousa chinensis* (Indo-Pacific humpbacked dolphin) and ten other topics. Furthermore, the overall study of the project was conducted based on these additional studies. Therefore, it can be concluded that mega infrastructure construction principal-agent relationships fully reflect project goals, subjects' behaviors, management element associations, external environments, and coordination of integrated relationships.
2. *Dynamics of Principal-Agent Relationships*

   Because there are many mega infrastructure construction participants and substantial changes in main management tasks occur in different stages, project managers must authorize different subjects to participate in construction management activities according to different assignments at various stages, thus forming a dynamic principal-agent chain composed of different subjects. In fact, it is a dynamic reorganization and evolution of mega infrastructure construction management organizational platforms.
3. *Duality of Principal-Agent's Dominant Position*

   When the rights and the functions shift from the upper to the lower construction management organization levels, every principal-agent subject (except the one at the very top and the one at the very bottom) is a principal and an agent at the same time. For instance, a project manager is an agent for the government, but he is a principal for the construction organization. As an agent, the project manager usually has political responsibilities and is responsible for the historical mission, while as a principal, he has information advantages and the motivation to seek information to maximize his own utility. The government's role is also a dual one. When it works as an agent, it represents the citizens' powerful decision-making right and voices. However, when it works as a principal, its role is to authorize relevant departments and professional institutions to conduct functions related to administrative responsibilities or contract forms. At this time, mega infrastructure construction management principal-agent relationships assume standard principal-agent functions, and an agent contract is established on the basis of free choice and the clarification of rights and interests.

6.5.3 *Hierarchical Mechanism of the Mega Infrastructure Construction Principal-Agent Relationship*

In one sense, hierarchy refers to various grades and levels. The reason the mega infrastructure construction principal-agent relationship is a hierarchical process is that the relationships between mega infrastructure construction subjects are relatively stable, as they are formed gradually level by level. Furthermore, the multilevel principal-agent chain in the structures previously discussed is denoted by a more essential mechanism and property. However, hierarchy also means transition and transportation. During the process of mega infrastructure construction, there exists the transmission and transportation of materials and information flows among various subjects. Regarding the transmission of different flows among the mega infrastructure construction principal-agent relationships, first, the relationship flows from principals to agents differ from those from agents to principals. For example, when the government engages in transmissions with professional institutions, the government generally transmits, as a principal, fund and information flows, whereas when professional institutions work as agents, they mainly transmit knowledge and technology flows. Second, the procedure whereby funds and information flow from social citizens who work as initial principals to various levels of government agencies and project managers before reaching construction institutions who work as the terminal agents is also the procedure, whereby fund flows and information flows are gradually utilized by and transformed in the construction entity (presented in Fig. 6.6).

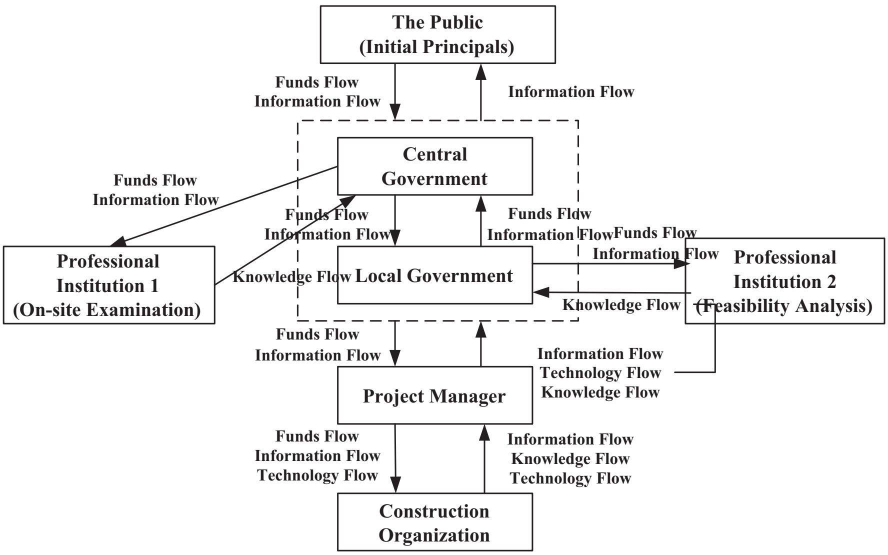

Fig. 6.6 The transmission of hierarchical agency flow of mega infrastructure construction

Finally, an important issue that must be explained is that current mega infrastructure construction is a time activity in the market economy. For instance, people's behavior patterns and concepts are restricted and influenced greatly by the rules of the market economy, as are the integrations and allocations of construction resources and the decisions and behaviors of construction contractors (Holt et al. 1994; Holt et al. 1995; Hatush and Skitmore 1997; Fong and Choi 2000; Lam et al. 2000; Shen et al. 2003; Zhou 2009; Nureize and Watada 2011). Furthermore, the mega infrastructure construction entity reflects the nature of not only public goods but also of commodities. For example, construction investments and finance patterns and operations abide by financial market rules; however, after construction completion, they may then adopt market operation models with respect to charging and loan paying. Therefore, mega infrastructure construction principal-agent relationships are conducted in the market environment, and thus, a more accurate summation is a perception of *mega infrastructure construction principal-agent principles of the government pattern in market conditions*.

6.6 Logical Connection Analysis of Basic Principles

On the foundation of the five basic principles mentioned above, a logical analysis of the connections among the principles is conducted.

According to theoretical thinking principles, if we conduct the abstract analysis of the phenomena and issues of mega infrastructure construction management activities and abstract the two most fundamental and most common elements, we find subject and complexity.

A subject is a person who plays a leading role in mega infrastructure construction management activities and who possesses cognitive and practical abilities. *Without a subject, mega infrastructure construction management activities will not realize their full potential or meet expectations.*

Complexity is the most important property of the mega infrastructure construction management activities, and as such, it can reflect the essential characteristics of the management object and the object property in mega infrastructure construction management. *Without complexity, mega infrastructure construction management activities will not achieve their full potential or meet the intended expectations.*

Principles of mega infrastructure construction management theories not only fully reflect the nature of mega infrastructure construction management activities through the perceptions of the properties of theoretical thinking but also adequately embody features of mega infrastructure construction management activities with the intention of enhancing the value of construction thinking. In addition, the two concepts contribute to the realization of the logicalization of theories. Therefore, principles of mega infrastructure construction management activities must fully disclose the basic rules of subjects' behaviors and objects' characteristics regarding subject and complexity, the two most fundamental but also most common elements. Whether this can be realized is a major criterion for measuring the academic quality of the principles of mega infrastructure construction management theories.

In this chapter, five basic principles have been advanced, namely, degradation of complexity, adaptive selection, multi-scale management, iterative generation, and hierarchical principal-agent relationships.

First, according to the mutual conversion rules of mega infrastructure construction complexity among its physical backgrounds, systematic connotations, and management activities, the important role of this property, namely, complexity, in mega infrastructure construction management activities has been emphasized. Nevertheless, principles of the degradation of complexity advanced the notion that by fully utilizing the variability of the recognition of construction virtual complexity, subjects can degrade or decompose the complexity suitably and reasonably with the aim of relieving subjects' difficulties and inabilities during the process of knowing complexity. This is the most fundamental behavioral principle and dominant goal of subjects during the implementation of mega infrastructure construction management activities.

The adaptability of subjects' behaviors not only leads to complexity but also becomes a means of dealing with such complexity. Consequently, subjects could create a type of behavioral principle that is part of the main form of adaptive selection and is at the level of management operations by embedding adaptive principles into the selection process related to construction decision programs, organization patterns, contractors, suppliers, and other practical issues. As a result, these behaviors are more operational and enforceable than are the principles under the concept of the degradation of complexity.

In addition, according to the principles of the degradation of complexity, subjects could conduct a necessary scale division of multi-scale phenomena related to ubiquitous management activities and analyze the influence of different scale characteristics of management issues, actions that could result in the refinement of the management of the element of complexity. Thus, on this basis, multi-scale management activities are conducted correspondingly.

Under the joint influence of the adaptive selections of the subjects and the multi-scale management, the subjects' behaviors, with respect to complexity degradation, are compelled to adhere to the rules, thus enhancing the degree of matching and the operability between subjects' behaviors and complexity characteristics and improving the subjects' abilities to cope with complexity and its effects.

Further, all behaviors of the mega infrastructure construction management subjects and all of the goals of those behaviors are intended to design and advance programs that can solve complex management issues. Consequently, in practical management activities, the complexity of the issues is decomposed into different stages of the program generation process under the principle of complexity degradation, according to the limitations of the subject's capabilities. Thus, the complexity that subjects confront in each stage represents only a portion of the whole complexity, where the aim is to obtain certain phasic solutions with relatively low difficulty and then create a program sequence of all programs from the different stages. Following this, an iteration of this sequence is used to incorporate programs related to the whole stage. The subject's iterative generation program, in practice, reflects not only the principle of complexity degradation but also the principle of adaptive selection, which is a form of the common and practical operational mode of the actual management activities.

Thus, under the direction of the complex degradation theories, the principles of subjects' behaviors, which are operational, have been formed from different angles through adaptive selection and multi-scale management, whereas the iterative generation method is the general rule of subjects' management behaviors and operation means, which are formed based on the combination of the three principles mentioned herein.

Finally, hierarchical principal-agent relationships maintain the organizational structure of mega infrastructure construction management subject groups and stabilize that structure. For example, all contractual relationships, such as those between principal and trustee and agent and client as well as those between internal subjects of the group, are the basic guarantee of the platform structure and the overall capabilities of the mega infrastructure construction management organization. Furthermore, these relationships are the basic principles that maintain the efficiency of organizational platforms. Based on this principle, the constitution of the subjects and the behavioral principles of the mega infrastructure construction management organization and the organization management mechanism design has a certain theoretical foundation.

Thus, the five basic principles put forward in this chapter are derived from mega infrastructure construction management practice and are close to the two fundamental management elements, namely, subject and complexity. As such, they fully reveal logical relationships in mega infrastructure construction management phenomena, basic rules of causal relationships, and subjects' behavioral principles and operational principles of universality, all of which exhibit close correlations with one another.

Specifically, from the perspective of the essential property, namely, mega infrastructure construction management complexity, subjects' leading behavioral principles with respect to complexity degradation are first established in the cognitive stage for subjects through the adaptability of the perception of construction virtuality in the conflict between management complexity and the subjects' controlling complexity. To improve the practical operability of subjects' management behaviors, adaptive selection and multi-scale management are used to develop subjects' behavioral operation principles from the aspect of the improvement of subjects' behavioral capabilities and the degradation of inherent complexity. Under the joint influence of these principles, a type of iterative method has become the general pattern for the generation of subject management behavior. All of these are implemented, completed on the management organizational platform, and formed based on the hierarchical principal-agent contractual relationship subject groups. In this way, various types of hierarchical principal-agent contractual relationships have become the fundamental dynamic principles for the operating mechanism of the mega infrastructure construction management organizational platform. This indicates that whether centered on subject or complexity, the five basic principles mentioned herein constitute the basic principle systems of the localization of the mega infrastructure construction management theory system, as presented in Fig. 6.7. Based on this, the concepts and basic principles mentioned herein can be used to further describe and deduce scientific issues that have academic qualities and theoretical values related to mega infrastructure construction management.

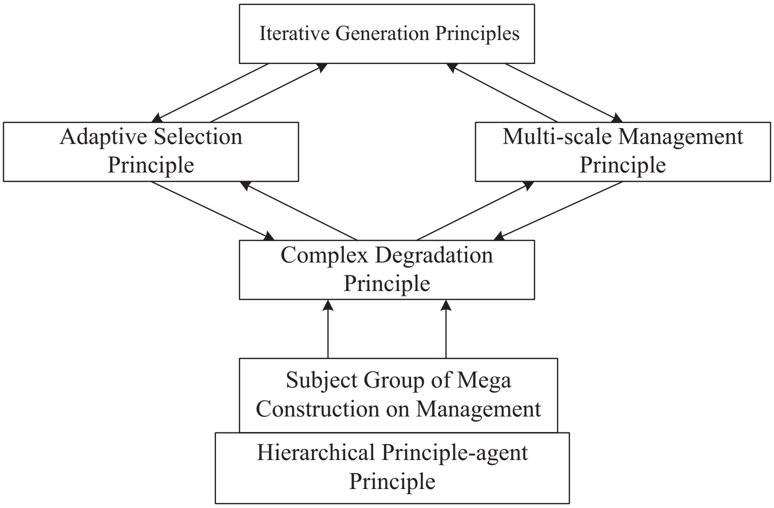

Fig. 6.7 Logical correlations of basic principles

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Chapter 7
The Scientific Problems with the Mega Infrastructure Construction Management Theory

The general connotation and significance of the scientific problems associated with the theory system have been elaborated in Sect. 4.4. Now, based on the core concepts and rationales discussed in Chaps. 5 and 6, we employ the core concepts and make deductions based on the explicit rationales to identify the academic scientific problems and their theoretical values with respect to the mega infrastructure construction management theory. Although this is only a tentative exploration of the building of scientific problems in the mega infrastructure construction management theory system, its significance is far more important because only after the establishment of the complete logic chain, i.e., core concepts—rationales—scientific problems, can the mega infrastructure construction management theory system be perceived as generally normative and complete.

Theoretical scientific problems place greater emphasis on the abstraction and universality of the connotation combined with the derivative function of the core problems. That is, the problems focus more on revealing the essence of the connotation and compacting the basic laws at a theoretical thinking level. Therefore, it is advanced herein that scientific questions should embody normative and complete formation paths of the theory system. Moreover, the concentration herein is on determining how to define, describe, and analyze the academic ideas and general technical routes regarding the connotation and content of scientific problems. However, it is not feasible to research every scientific problem and draw in-depth and elaborate research conclusions. Thus, even the choices and abstractions of the scientific problems are the result of the author's personal perspectives.

In fact, according to the objective law of theory development, the issues regarding what scientific problems should be involved in the theory system of a subject area and what problems are the most central and radical, on the one hand, depend on the degree of practice within this area because practice is the source of theory. On the other hand, they rely on the maturity level of the theory system in that the system offers scientific problems a favorable academic environment. Thus, the significance of the several scientific problems put forward in this book reflects merely

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an attitude that supports the exploration of mega infrastructure construction management theory. It does not mean that the description and explanation of these problems are developed and complete. Rather, there is great potential for scholars in the field of construction management to focus on the establishment and perfection of the scientific problems in a mega infrastructure construction management theory system.

This chapter tentatively proposes six basic scientific problems that involve the organization, decision-making, site, financial engineering, technical management, and risks of mega infrastructure construction, all of which span the practice activities of mega infrastructure construction management.

7.1 The Management Organization Mode and Dynamic Analysis in Mega Infrastructure Construction

Similar to the management activities in other fields, the two most basic elements of mega infrastructure construction management activities are the management subject and the management object. The management organization of mega infrastructure construction is a system composed of management groups whose management function is directed toward management objects. The management organization mode consists of system forms such as the subject composition of an organization, the configuration of management authority, management processes, organizational structure, management support, and the formation mechanism that guides the organization's overall management behavior (Sheng 2009). Obviously, management organization of mega infrastructure construction and its organization patterns are the two primary scientific problems in mega infrastructure construction management theory.

Specifically, the theoretical problems regarding the research on management organization and organizational modes in mega infrastructure construction include:

1. The formation and features of management organization in mega infrastructure construction
2. The basic functions and structures of management organization in mega infrastructure construction
3. The dynamic analysis of management organization in mega infrastructure construction
4. The emergence of macro behaviors and functions from micro subject behaviors within the management organization of mega infrastructure construction through the organization and self-organization mechanism under meso modes

These problems are perceived and thus studied as scientific problems in mega infrastructure construction management theory for the following reasons:

1. These problems are deeply rooted in a background of mega infrastructure construction management practice.

2. All studies of these problems adhere to the thinking principle of complexity as a whole.
3. These problems are described by references to the core concepts presented in Chaps. 5 and 6 of the book and are deduced by relevant rationales that embody and guarantee the completeness of the formation path of mega infrastructure construction management theory.

7.1.1 An Overview of the Management Organization Mode in Mega Infrastructure Construction

In Sect. 2.4, we noted that mega infrastructure construction management activities constitute the management subject and organization through three platforms, namely, the decision-making subject platform, aggregate decision supporting platform, and aggregate executive system platform. Each platform, by nature, is a complex, self-adapting system. The interrelation and coupling among the platforms form a more complex management organization system with a hierarchical pattern in mega infrastructure construction. This newly formed system is a complex, systematic system that then assumes a complex system as its subsystem, i.e., a complex system of a system. This is our cognition regarding the essence of the management organization system and the complexity attribute of mega infrastructure construction (Kapsali 2011) .

Furthermore, in Sect. 5.2.2, it was stated that the main functions of any kinds of management organization of mega infrastructure construction do not directly provide specific methods and programs related to management problems in mega infrastructure construction. Rather, they provide the appropriate environment and conditions for the development of methods and schemes. Therefore, the subjects in the management organization of mega infrastructure construction, especially the core subject, should complete the following tasks (Sun and Zhang 2011):

1. Dynamically select and combine the subjects in the subject group in such a way that the group will optimize the functions of the organization and will adapt self-organization strategies that allow the subject group to develop the ability to address management complexity in accordance with the requirements of different problems, in other words to manage the environmental (system) design of the management organization in mega infrastructure construction.
2. Formulate the operating rules and processes that support the formation, operation, and development of the abilities of the subject group. This is, more specifically, the conditions and mechanism design of the management organization in mega infrastructure construction.

The understanding is that the management organization is a type of platform in mega infrastructure construction that exhibits the characteristics of self-organization and self-adaption within the management organization of mega infrastructure construction (Hoda and Murugesan 2016; Takeuchi and Nonaka 1986; Sheng and Zhang 2011). As a complex, systematic system, the management organization in mega infrastructure construction does not adhere to the simple system principle that "many hands make light work." Rather, it is oriented to establish and improve the overall ability of the organization to select optimal subjects and to enhance the levels of routine power, professionalism, relations, abilities, knowledge, and mutual perceptions of these optimal subjects to reflect the other organization behavior required of the management organization of mega infrastructure construction.

Furthermore, as a complex system, the management organization in mega infrastructure construction should pay sufficient attention to the design of the management mechanism and process and to the routine power configuration of the management organization in construction to enhance the internal organization's ability to manage the complexity. This combination of such ability and power is not only more powerful than that of only one or the other, but it also incorporates the superposition of the two. In this way, it reflects the self-adapting and self-organizing behaviors of the management organization in mega infrastructure construction. As a complex, systematic system, the management organization in mega infrastructure construction and the formation of its overall behavioral ability, especially the formation of the ability to manage and control the complexity of the management subjects, involves the behavioral emergence of the combined action of other-organizing and self-organizing behaviors within the management organization whereby the self-adapting and self-organizing mechanisms play essential roles.

It is assumed that if the functions and decision-making ability of the management organization of mega infrastructure construction are formed by other organizational entities, such as static structures or functional requirements of the organization, and have no self-organizing or self-adapting abilities, the management organization of mega infrastructure construction is not equipped with the capacity to manage the complexity due to its dynamic evolution, and as such, it is neither predictable nor stipulated (Lu et al. 2015a; Bosch-Rekveldt et al. 2011; Gransberg et al. 2013).

Accordingly, the following scientific problems are particularly essential and significant:

1. How does one select the subjects and optimize their skills in management organization of mega infrastructure construction? What are the requisite attributes of management subjects and what are the expected functions of these subjects?
2. Given that the structure of the organization should be stable so the subjects can perform basic management functions, what is the correlation between management subjects and the basic structure of the organization?
3. More importantly, this structure should possess self-organizing and self-adapting functions. That is, between the micro level of the subject and the macro level of the organization, there exists a new formation of behaviors and abilities as well as their transformation and emergence. In essence, this links the overall behavioral ability of the management organization to the individual micro behaviors that can be explained by individual behaviors, but at the same time, it cannot be determined

whether the overall behavioral ability is the result of a simple joint effort of individual behaviors that can be completely and clearly explained by these individual behaviors. The growth, expansion, and derived abilities are due to the emergence of the so-called overall behaviors of the organization. What is most important with respect to the design and optimization of the management organization in mega infrastructure construction should be the design of the self-organizing mechanism as it can produce new abilities and strategies for managing complexity.

7.1.2 Analysis of Management Organization Mode of in Mega Infrastructure Construction

According to the principle of engineering thinking, different management organizations of mega infrastructure construction should have different types of routine power, relational structure, and overall ability. Subjects with different attributes or those with the same attributes but with different levels of skills will both directly influence the management organization's corresponding behaviors and abilities (Mok et al. 2015). For example, a subject who possesses an attribute or skill for routine power directly impacts whether the management organization can reasonably and legally make corresponding decisions, whereas subjects whose attributes are related specifically to ability directly influence whether the management organization can put forward a high-quality decision-making plan. Generally, we must consider what type of subjects possesses the necessary routine power to tackle the corresponding management problems in accordance with the peculiarity of the problems because both the deficiency and the redundancy of management routine power, which would increase the waste of management routine power and management costs, should be avoided.

Accordingly, the management process, management routine power configuration, and conversion mode of various types of management resources within the management organization of mega infrastructure construction act as the running process and the operating principle of a machine. That is, the operating mechanism and management organization produce the ability to handle the complexity of management problems, a process referred to as the organization mode of the mega infrastructure construction management organization.

In Chinese, 模 refers to the principles, regulations, and methods adopted to maintain the existence and stability of objects, whereas 模式 refers to the abstraction and standardization of these principles, regulations, and methods.

In other words, the management organization mode of mega infrastructure construction refers to the individual quality and code of conduct of the management organization of mega infrastructure construction as well as the formation mechanism of the overall function of the organization. Among the mechanisms, it is particularly crucial to determine the type of mechanism that can activate the self-adapting and self-organizing ability of the management organization and drive the organization to promote its integrity.

Because the government is generally the decision-making and investment subject in mega infrastructure construction, the management organization inevitably tends to exhibit features of strong dominance governed by power (Levitt 2011; ASCE 2009). Additionally, within the organization, every type of subject has a certain type of power or resource, and in practice, power and resources are mutually transferable and employable. Therefore, the management organization in mega infrastructure construction must be concerned with the comprehensive engineering targets and must coordinate the interests and the behavior relations of many parties during the process of which the distribution and execution principles of various types of power are the key elements.

The general types of power within the management organizations of mega infrastructure construction include administrative power, routine power, financial power, and executive power. Among them, administrative power is a public power, which means that the public delegates the government (or the administrative branch of the government) to manage the mega infrastructure construction and offer public services within the scope of the law. Routine power means that the administrative department can decide, manage, and supervise a certain class of specific activities and responsibilities according to associated regulations in mega infrastructure constructions. With respect to financial power, the subjects have ownership and allocate power over the finances and property of mega infrastructure construction. Executive power refers to the power the subjects execute within the management organization, and it includes the monitoring of decisions and the establishment and management of schemes to be implemented throughout the mega infrastructure construction process.

In general, the allocation of power in the management organization mode of mega infrastructure construction has its own principles, such as a reasonable and legal system for delegating power and support. However, this delegation may be deeply influenced by the economic, social, and cultural environments. In particular, the subjects' skills and abilities regarding construction management and the ways to compensate for deficiencies in these abilities should be taken into consideration when identifying the management organization mode (Li et al. 2011; Chang and Shen 2013; Qian 2013).

For example, in mega traffic engineering construction, a variety of conditions caused by various environmental and regional factors materialize in the management organization mode. However, even within the same area, different management organization modes would appear due to the differences between the economic development levels and the traditional management habits throughout China's huge area and the large differences between economic development levels and the abilities of the engineering enterprises. The mega traffic engineering construction in China mainly has three management organization modes.

The first mode is self-management dominated by the government (temporary command). In this situation, the legal person in construction management, which was organized by the government, is responsible for all work associated with construction management. Thus, the government plays the role of the project owner and directly assumes control of the organization and management of the

Table 7.1 The leading pattern attributes of China's major project organization management scheme

		Mode of self-management	Mode of project entity	Agent-construction system
Allocation of correlated power	Administrative power	Central government Local government	Central government Local government	Central government Local government
	Routine power	Department of Industry	Department of Industry	Department of Industry
	Economic power	Local government	Local government or local financing platform	Local government or local financing platform
	Executive power	Headquarters provisionally built by the government	Project company with legal entity status	Professional team entrusted by bidding approach
Engineering environment	Economic power	Planned economy	Rapid development of market economy	Marketization
	Technical environment	Hard technology (assembly, design, construction technology, material) Soft technology (construction, construction, and management ability) integrated by the government	The project company responsible for the project construction generally possesses the necessary hard technology and soft technology	Temporarily lacks long-term stable and specialized project construction team
	Legal environment	Laws and regulations related to project construction; policies remain imperfect	Laws and regulations related to the project construction are increasingly sound	Laws and regulations related to the project construction are increasingly sound

construction projects and comprehensively monitors the quality, safety, cost, and schedule of the construction project. Accordingly, the government should establish temporary project construction headquarters to manage and oversee the needs of the construction and recruit project management personnel (management personnel form all units of the construction industry in China) to conduct the organization and management of the project's construction. In this mode of self-management dominated by the government, the administrative power, the governance, and the property rights are controlled by the government, while the executive power is the responsibility of the headquarters organized by the government, and as such, the headquarters are dissolved upon the completion of the project. This model recognizes the full capabilities of the administrative power, such as the efficient integration and allocation of resources, the concentration of forces on a major task, and the assurance of the maximum effectiveness of the government's management of the public goods in major projects. However, the model is also prone to the excessive and inappropriate intervention from the public power, the excessive intervention of project construction, and the possible interference with the objective law of construction. With the implementation of the project's legal system, the mode of self-management dominated by the government (temporary command) has rapidly declined.

The second mode is the legal entity mode. The legal entity of construction management is responsible for the project and for the legal issues related to construction management per the contract. The primary understanding is that the legal entity has the ability of independent construction, self-management, and self-development and is responsible for organizing, coordinating, and managing the project's quality, safety, processes, and costs associated with the areas of design, construction, and maintenance. An organization management mode based on a legal entity responsibility system is more common in the construction of large-scale, complex technology projects.

The third model is the agent-construction system. Under the agent-construction system, when the project sponsor or the legal entity of the construction management does not have sufficient professional management ability, agent-construction units are developed, and agent contracts are signed and enforced to entrust the units to conduct the work of the construction management through tender and other means. A comparison of these three modes is presented in Table 7.1

7.1.3 Basic Force System of Mega Infrastructure Construction Management Organization

The management organization of mega infrastructure construction is a complex, systematic system comprised of basic structures and basic functions. Moreover, it regards social beings as elements who possess the ability to manage and control complex management problems.

Constituted by the stakeholders with different skill levels and attributes, for the organization to exhibit the ability referred to as integrity, the organization must have its own inherent mechanism. Beginning with the management feature of mega infrastructure construction, only if the basic mechanism is clear can the general law behind the design, analysis, and optimization of management organization in mega infrastructure construction be mastered and the feasible and effective management organization modes be provided.

Originally, before the development of the management organization, each stakeholder of the management organization in mega infrastructure construction was independent and discrete and had not direct relationships with the other stakeholders. However, once they become individual elements of the management organization of mega infrastructure construction, every stakeholder, though independent, was also part of a correlated group. Thus, the independence and discreteness are no longer the primary attributes of the stakeholder, but the relationships established between and among the individuals instead become a primary attribute. This constitutes a drastic change in the management organization of mega infrastructure construction when comparing the structure of mega infrastructure construction before the development of the management organization and after its formation. Moreover, many resulting complex organizational phenomena and problems followed the establishment of the management organization.

It is generally known that two originally independent individuals establish a relationship through various means. For example, the administrative power, routine power, allocation power, and executive power within the management organization of construction are all part of a cohesive mix of individuals.

The present problem lies in whether we can establish a specific term to depict this phenomenon on a more generalized and elemental level. For many years, scholars have found that it is a universal phenomenon in the nature of human society that the originally independent distinct individuals are joined by a certain adhesive that then results in the establishment of a certain correlation. For different situations, people use different concepts to describe this adhesion phenomenon, but the most commonly used and intuitive concept is that of force between objects, as in the area of physics, such as gravitational interaction, friction, magnetic force, and nuclear force. Thus, various types of different adhesive features and rationales have been developed.

Based on the unified cognition perspective from physics to biology and then to sociology, the generalized association between factors in the system can be explained using the concept of force. Ouyang, in the *Foundations of Complex-System Theories* (1999), stated, "In order to form a system, the cohesive effect between the individuals in a set must be strong enough...If the cohesive force is stronger than the separated individual force or the force transferred from an individual to an external element, this set will form an integral structure and become a combined system on a much grander scale."

According to this academic concept, there must exist an adhesive within construction management organizations either generated by the external world or from within the organizations themselves. Otherwise, each individual will unavoidably be an independent and discrete entity.

Thus, in a general sense, we employ the concept of force to describe the interrelations among the individuals in the management organization of mega infrastructure construction. Since the individuals in the organization are human, the force should not only follow the rationales of the social sciences and humanities but should also demonstrate the special connotation of management with respect to mega infrastructure construction, rather than simply applying the concepts of mechanical force and atomic force as they relate to physics. Specifically, the force between and among individuals in the management organization of mega infrastructure construction should obey the governmental principal-agent theory under the market economy condition, which is a force that is deeply influenced by the dual tensions between the government and the market.

Thus, we conclude and present the following views:

1. The management organization is composed of many mega infrastructure construction subjects, such as all levels of government, specific government departments, owners, contractors, suppliers, supervisors, R&D institutions, colleges, and the public.
2. With respect to force, subjects inside the management organization of mega infrastructure construction generally follow the effect or influence of the governmental principal-agent theory under the market condition (Zhang and Sheng 2014), such as administrative power, economic power, legal power, contractual power, and cultural power, and then synthetically form the system of force on the individual and the integrated levels (Taucean et al. 2016).
3. In management organization, the concept of force not only has different connotations and attributes, but it also demonstrate varied dynamics and evolution in different cases (Dosi and Marengo 2015), which is a root cause of the complexity of the functions of the management organization as well as the overall behaviors of the organization.

Our introduction of the concept of force in the studies on management organization and organization modes of mega infrastructure construction is a visualized statement about the correlation of the internal system of mega infrastructure construction. However, in actual management, various types of interrelations, influences, and effects among the subjects in the management organization cannot be measured as a physical force, and thus, it is difficult for the concept to be directly perceived and clearly defined. Accordingly, the concept of force is introduced based on the knowledge of physics and visualized methods to facilitate the discourse of organization in mega infrastructure construction, thus making it easier to understand the behavioral mechanism at play among individuals on a micro level with respect to the management organization of mega infrastructure construction.

Accordingly, the following three points are of particular importance:

1. The effect of force among the subjects in the management organization on mega infrastructure construction must be strong and stable. If it is not, the subjects will not be able to maintain their interrelations nor will the organization be able to develop a stable structure.

2. The effect of force among the subjects on the management organization of mega infrastructure construction exhibits not only in strength but also in the types of force, its characteristics, and its morphological diversity. More precisely, it is this diversity that causes the management organization to adopt and reflect different functions.
3. The function of the management organization of mega infrastructure construction is to represent, on a behavioral level, the overall sense of the organization. Accordingly, it is closely connected to not only the mutual effect, variety, features, and forms of the force among organization subjects but also the external environment and the internal self-organizing forms. This suggests that the function on the macro level of management organization can inevitably be formed through the individual conditions and behaviors on a micro level, whereas the forms and mechanism can be created on a meso level, thus representing the hierarchical effect of the mechanics within the organization.

The several meanings of force as presented within the management organization of mega infrastructure construction are as follows:

1. Administrative Power

Administrative power (public power) refers to the power of human communities, such as nations, to organize, command, and manage their members, make decisions, and pass and execute laws with respect to community affairs. Legal public power is, by nature, the transference of partial power to members of society or the authorization of members of the public to act within limits. It follows that administrative power is authorized by the public and is actually the power of public groups and persons in charge for the purpose of maintaining public interests and developing public affairs. It classically manifests as the coercive power executed by state organs based on public will, which means that this power is institutionalized and legalized (Ruuska et al. 2011).

Accordingly, administrative power has three primary characteristics. First, publicity is the core of administrative power, which means that administrative power is a form of public power rather than private or exclusive power; second, the object of administrative power should be related to public affairs rather than private affairs; third, administrative power is responsible to the public and serves the public interests. Public power cannot be alienated or transformed into private power.

Administrative power refers to public power, and as such, it conveys public will and is executed by state administrative organs within the management organization of mega infrastructure construction.

Mega infrastructure construction is a public good that represents expansive social and public interests, and it is a carrier that best represents social public needs and interests. During the course of the decision-making process and the establishment and operation of mega infrastructure construction, the state (government), which represents the social public interests and is entrusted by the public, should exercise all necessary public affair management power with respect to scientific decision-making and the management of mega infrastructure construction from the public perspective (Patanakul et al. 2016). In other words, in the decision-making and management activities of mega infrastructure construction, public power enjoys a vital and indispensable status and effect. Moreover, public power cannot be alienated or transformed into private power during its execution. In practice, during the early stages of the decision-making process of mega infrastructure construction, administrative power is especially important and powerful.

2. Economic Power

Mega infrastructure construction is a system integrated by a variety of resources, a large part of which can be acquired through market economic activities and the exchange of currencies. That is, during the establishment of mega infrastructure construction, the transfer and exchange of economic benefits under the market's economic conditions are not only the important ways for mega infrastructure construction to realize resource integration and allocation, but they also guarantee a stable and effective relation among the subjects of the management organization in mega infrastructure construction, and from among which the transfer of economic benefits, especially the currency payment of benefits, is most important.

By comparison, administrative power represents the social public power, whereas economic power represents the private power of market activities. The management activities of mega infrastructure construction under market conditions simultaneously reveal administrative and economic powers, which is the foundation for the engineering management organization based on the governmental principal-agent theory under market conditions and the root cause for mega infrastructure construction's representation of the dual attributes of public goods and commodities on different levels.

Economic power refers to the correlation interaction created by the subjects within the organization of mega infrastructure construction through the transfer and exchange of economic interests.

3. Legal Power

Today's society is constantly being perfected. Within the legal environment, all countries have formulated a series of specialized laws and regulations to guide the decision-making of mega infrastructure construction and construction management. There are clear stipulations in the laws and regulations regarding decision-making and subjects' behaviors within the field of mega infrastructure construction, relations among subjects within the construction management organization and special interactions and business dealings during the various stages of construction management. Through the application of significant coercive and constrained force, the above have become the behavioral norms of the establishment and the management subjects within the management organization of mega infrastructure construction.

Legal power refers to the power of the coercive and constrained laws and regulations that are manifested via the behaviors of the subjects within the organization of mega infrastructure construction.

4. Contractual Force

A contract was, originally, a type of social agreement created as a result of the free negotiations among subjects according to the law. Thus, it is a free agreement between two or more parties. The subjects involved in the contract enjoy the same status and have equal rights and obligations, and no one has privilege beyond the contract.

Maintaining faith is the soul of contract behavior. Its manifestation is such that when signing a contract, both contracting parties commit to being honest, not concealing the truth, not being malicious, and responsibly fulfilling the contract. When these behaviors habitually become ethics, the spirit of the contract is formed. As spirit is a psychic power, the force of the contract is the power of the contract spirit.

The spirit of the contract as formed originally in private law has been extended into the area of public law and social interpersonal relationships. The spirit of the contract then overlaps, and the public and private laws are developed. Such laws include not abusing public power, not exerting random and micro interventions on the freedoms and equality of the contract between individuals, and remaining neutral in the face of private contracts.

The relationships of the subjects in the management organization of mega infrastructure construction include both the contractual relationship between and among individuals, such as individuals and enterprises, in market activities and those relationships that overlap public and private laws and intersect administrative power. Therefore, whether the government, owners, contractors, suppliers, and social public abide by the spirit of the contract relates to the stability of the structure of the management organization, the performance of normal functions, and even the issues of modern engineering civilization such that public power will not be alienated and the construction subjects carry forward the social responsibility (Hou 2008).

The force of the contract is different from that of administrative, economic, and legal powers. In today's modern social environment, the spirit of the contract has been cultivated to represent the modern civilized ethics of the subject in the management organization and the behavioral criteria of citizens in mega infrastructure construction. In this sense, it is a significant stimulative and constrained force.

5. Cultural Force

Culture is the general term that refers to man's mental activities and his products. It is the spiritual form of the development of human civilization. In today's society, culture has become an important resource for society, economy, and management in mega infrastructure construction. Accordingly, cultural *force represents the power of culture.*

Specifically, the cultural force among the subjects of the management organization in mega infrastructure construction integrates the following four parts:

(i) The common values, spiritual pursuit, and ethics shared by the subjects.
(ii) The ideas, such as self-learning and innovations, promoted by subjects as well as the joint collaborative power of behaviors.
(iii) The communication, strain, execution, and self-adapting abilities of subjects.
(iv) The social responsibility, citizenship, public identity, and social harmonious image presented by all subjects constitute the materialized cultural force (Baumgartner 2009; Martin 2001).

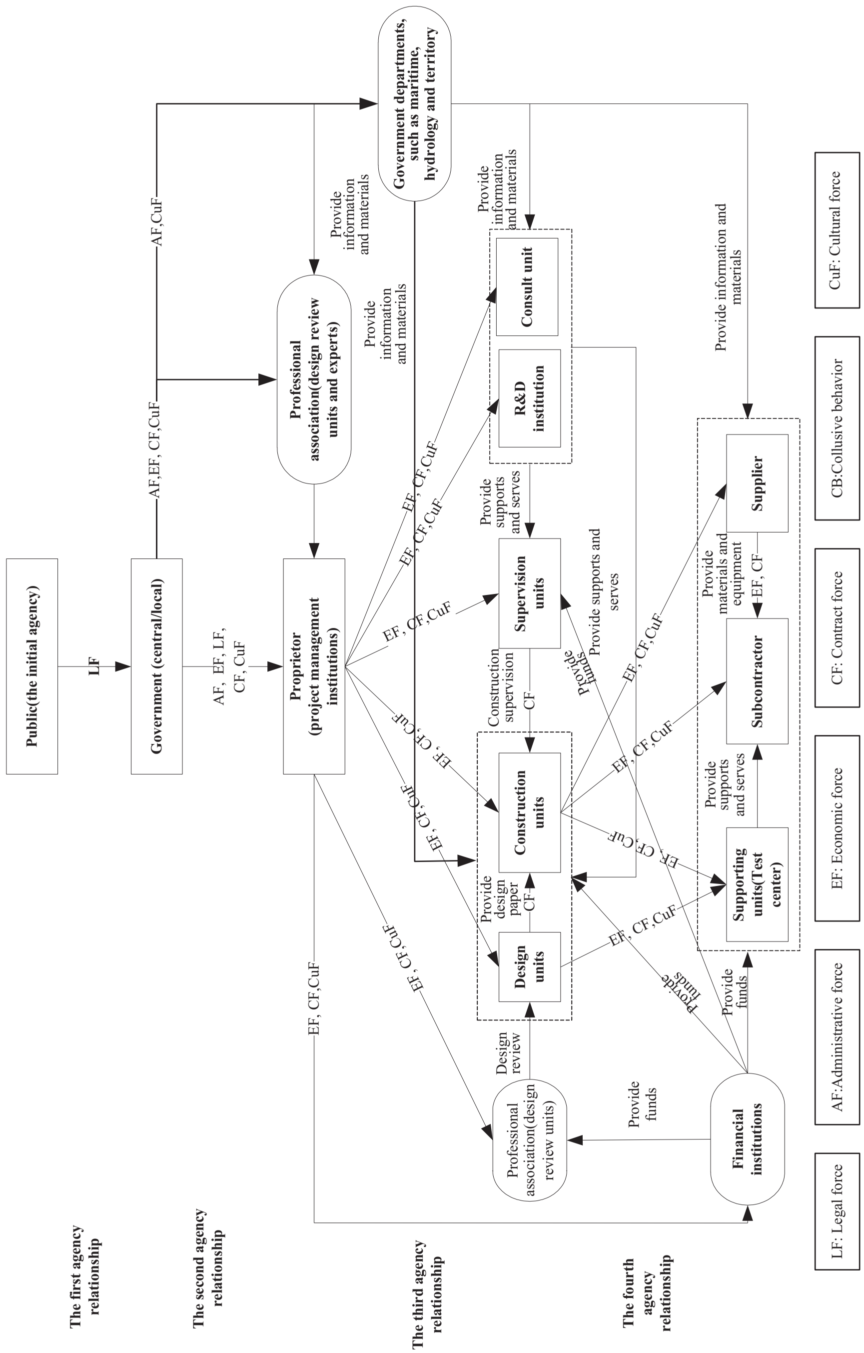

Fig. 7.1 Structure of forces of the management organization in mega infrastructure construction

Table 7.2 The types of force among mega infrastructure construction management organization subjects

Relationship among subjects	Types of force
Public-government	Legal force
Central government-local government	Administrative force, legal force, cultural power
Government-specialized institutions	Administrative force (or economic force), legal force, cultural force, contractual force
Government-project manager	Administrative force, economic force, legal force, cultural force, contractual force
Project manager-contractor	Economic force, legal force, cultural force, contractual force

Though these abilities mainly manifest as subjects' ethics and values, they also imply a strong power that has digested the subjects' values, condensed the will of the people and achieved unity. Accordingly, these abilities play an indispensable role in the implementation of administrative force and economic force.

The several types of force represented by the subjects of the management organization in mega infrastructure construction are presented in Table 7.2.

Figure 7.1 presents the structure of the system of force of the management organization in mega infrastructure construction.

When analyzing the interaction of the forces, the dynamic changes in the effects and the comprehensive effect among the subjects of the management organization, certain scientific problems regarding the management organization in mega infrastructure construction are concluded as follows:

1. How were the management organization modes formed in mega infrastructure construction and which mechanisms and principles of mechanics result in specific management organization modes?
2. To what degree did specific mechanisms and principles of mechanics affect the emergence of the overall behavior of the management organization in mega infrastructure construction?
3. To what degree did specific mechanisms and principles of mechanics affect typical organizational activities of the management organization in mega infrastructure construction, such as the dynamic analysis of subjects?
4. How should the principle of dynamics be applied to realize the governance of management organization in mega infrastructure construction?

7.1.4 Complex Forms of the System of Force Regarding the Subjects of the Management Organization in Mega Infrastructure Construction

Merely noting that there are many types of force impacting subjects is not sufficient. It is more important to identify the complex forms of force that exist among subjects and determine how self-organizations based on these complex forms represent the complex behaviors and functions, on a comprehensive level, of a management organization in mega infrastructure construction.

Form refers to the outside shape, the inside structure, and the overall expression of the object. That is, it is the objective attribute of the object. As such, objects differ from one another in form. In general, cases, although the forms of objects are invariable, they could be altered for various reasons. However, they are generally local changes in quantity, whereas overall changes in quality infer that the object no longer retains its original characteristics. Additionally, although the subjects' force type has not changed, the subjects' self-organizing behaviors may result in the integration of important changes in the system (Bonabeau and Meyer 2001) .

At this point, the complex forms of the subjects' management organization in mega infrastructure construction require analysis.

Above all, every management organization in mega infrastructure construction is a complex artificial system composed of various subjects operating within specific environments. In addition to the natural geographical environment, other important environments include the political, social, economic, historical, and cultural environments in various countries and districts.

Because of this, the environment provides the subjects of the management organization with legal force, cultural force, and administrative force in mega infrastructure construction. As such, this includes both the support and the constraints for subjective behaviors. Even the economic force and the contractual force are deeply influenced by the environment.

With respect to the governmental principal-agent theory under the market condition, the management organization and the government (or government sectors) as subjects tend to be important enough to become core subjects in mega infrastructure construction. Regarding important management problems, such as early engineering decision-making and resource integration and allocation, the government holds strong decision-making power as well as routine power. Therefore, the mechanical form of the government subject in the construction organization exerts the most important influences on the formation of the integral behaviors and functions of the management organization.

The government, as the entrusted public affairs agent, must adhere to certain laws and procedures. Thus, the management organization has responsive decision-making and administrative powers with respect to mega infrastructure construction. However, the government is also a type of organization. In fact, the management organization in mega infrastructure construction represents the government or government department, that is, the social entity who exercises administrative power. This social entity is, first, an individual. Therefore, while exercising the administrative power of the management organization and conducting associated activities with other subjects in the construction industry, this representative of the government simultaneously represents the individual and independent psychological and behavioral preferences; culture and value orientations, such as personal memories, knowledge, information, perceptions, cognitions, judgment, learning, and innovation; and the capability to self-adapt to the environment (Jolivet and Navarre 1996).

In this way, regarding the actual management activities of the management organization, the government representative not only possesses its own administrative power, but it also combines the legal power, contractual power, cultural power, and personal preference, particularly the personal interest demands given market conditions. Furthermore, integrating the forces with certain supplementary elements is not as easy as the vector addition of forces in physics. Instead, the integration results in the formation of complex behaviors in the subjects from the perspective of sociology. For instance, whether the government respects and adheres to the constraints of legal power, whether it shows respect for the contractual spirit of private power in social interpersonal relationships, or whether it restrains, the micro intervention of public power in private power directly leads to changes in the properties of the power of government. Even worse, the government, as a representative agency, may abandon certain behaviors; that is, it may separate itself from the standards of public power for its own benefit and conspire with private engineering subjects. The changes in the forms of power of those individuals with administrative power are responsible for these phenomena, and as such, the manifestations of government representatives differ due to the differences in their personal morality and their legal awareness.

Furthermore, contractors, as a type of important subject of the management organization of mega infrastructure construction, are manifestations of individuals who represent the economy of the market, and thus, they tend to establish relationships with governments, owners, and suppliers based on economic and contractual powers. With respect to the differences in legal awareness, contractual spirit, and cultural values and given the joint actions of legal and cultural powers, different contractors exhibit different comprehensive forms of power, such as cutting corners and recklessly altering schemes to gain profits. Nonetheless, they all consider economic and contractual powers to be the cores of interrelations. Other types of subjects in the management organization exhibit similar diversity phenomena with respect to comprehensive forms of power.

Moreover, the comprehensive form of power of each subject in the management organization is neither static nor monotonous nor is its properties, strength, or sphere of influence of its synthetic action of power. This is because, in different situations, the behaviors, psychology, and social characteristics of every subject undergo self-organizing changes (Saynisch 2010).

Figure 7.2 reflects this phenomenon.

The left side of the diagram (Fig. 7.2) presents the original forms of power among governments, owners, and contractors in management organization. The overall behaviors and functions of the management organization are then represented as the governmental principal-agent relationship under the standardized market condition. The middle representation in Fig. 7.2 indicates that in reality, contractors transfer benefits to owners and government agents via economic means, which weakens the originally existing effect of legal and contractual powers and further causes the degradation of the previously existing functions, i.e., monitoring, control, and constraints, of governments and owners in the management organization. Furthermore, if the contractors increase the benefit transfer and the government

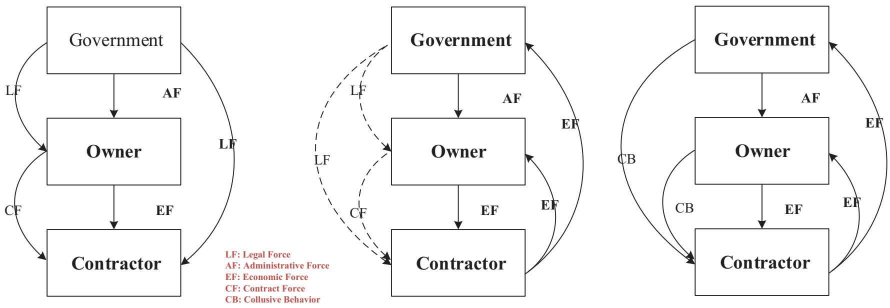

Fig. 7.2 The self-organizing organizations of the subject's force system in the management organization of mega infrastructure construction

representative severely lose the functions regulated by social public agents or if the owners abandon their behavioral standards, conspiratorial behaviors between two or more parties may emerge (see Fig. 7.2).

7.1.5 The Formation Mechanism of Organizational Behaviors of Management Organization in Mega Infrastructure Construction

Previous studies of major project management organizations have indicated that the most difficult problem is the transforming of micro individual behavior into macro organizational behavior. Thus, it is important to understand how the dynamic mechanism of the meso organizing mode works and the role that it plays.

The mechanical analysis of the main body of the management organization is a theoretical framework that was constructed specifically for this study. Because this is an exploration, it does not exclude other concepts and principles when analyzing the structures and connections between the main body of the management organization, and it thus conducts theoretical research on the management organization's major project mode on this basis.

In addition, even if this theoretical framework is established, it is difficult to realize any coherence among the micro individual behaviors of the organization, the organization's meso mode mechanism and its macro overall functions and then to illustrate how the behaviors among these are transmitted and transformed given that the behaviors on the three levels are no longer the result of a simple transformation. Rather, under the actions of self-organization and self-adaption, the functions of the three levels of the complex organization system emerge and disappear. Thus, it is essential that we focus on this problem by analyzing two specific mechanisms, namely, inner impetus and external impetus.

Inside the management organization of the construction industry, the *inner impetus* refers to the comprehensive form of the subjects' force system and its dynamic evolution based on the natural attribute, social attribute, and associate attribute of each subject, whereas the *external impetus* is the result of the interplay between the environment and the management organization of construction. Thus, jointly, these two types of impetuses give rise to the macro organizational behavior and functions of management organization, that is, the dynamic mechanism from the complex form of organizational micro individual force to the macro overall behavior and functions. Specifically, this mechanism is composed of two more basic mechanisms.

The first is the self-organizing mechanism, which includes the organizational ordered structure and the overall behavior or division and cooperation relationship among subjects. This behavior and cooperative relationship is motivated by goals that are actively and spontaneously formed by the subjects within the organization according to the correlation principles of the forces based on a mutual understanding whereby the subjects harmoniously engage in a special function of their own (Ye 1994; Kwak et al. 2015). This more complex mechanism, which is driven by an internal more basic mechanism, allows the management organization to evolve from a simple and general structure to a more complex and detailed one and to constantly improve the organization. This is called *the self-organizing mechanism or the self-organizing process of management in mega infrastructure construction*.

The self-organizing process of the management organization in mega infrastructure construction reflects man's adaptions as people are involved in the process, which explains the self-organizing changes in the structure and function of the management organization of mega infrastructure construction.

The second is the evolutionary mechanism, which originated from the external competition caused by certain constraints, such as resource constraints. For example, the management organization subjects' complex interactions during the self-organizing process expand from local interactions to global interactions are based on the type of force system. Furthermore, the organizing structures and operating modes of the management organization of mega infrastructure construction are constantly improving and promoting their ability to adapt to the environment.

With respect to the management organization in mega infrastructure construction, its overall behavior and the formation and evolution process of its functions depend on several aspects related to the interactions of the two basic mechanisms, such as the complex form of the force of each subject, the interaction modes and changes in degree of the subjects' force system, as well as the evolution paths for the macro structure and overall behavior of the management organization.

Thus, it is concluded that between the micro subjective level and the macro organizational level of management organization in mega infrastructure construction, there is a reciprocal process that assumes the various complex forms of the subjects' force as its basic elements. The elements constitute a meso dynamics principle that is somewhere between the micro level and the macro level. As such, this principle is the formation mechanism of the macro behaviors and functions of the management organization as well as the organization mode of the management organization in mega infrastructure construction.

At this point, a detailed analysis of the internal operation of this important process is necessary. First, as an individual, every subject possesses his original standard internal and external force systems regarding the various social and functional orientations. The internal force system is a system that links various forces between itself and other subjects within the organization, while the external force system is a type of system that relates various forces between itself and the external environment. As the two force systems are intercoupling and changing, they present a dynamic and evolutionary form. The form here includes not only the mode of force, its strength, and its direction but also the type of feedback and transformation among the forces. Given the interaction of forces, the entire form and evolutionary process are equivalent to the operating principle and the complete working process of a machine, whereby entire operating results constitute the overall behavior and function of the management organization.

Originally, when designing and establishing the management organization in mega infrastructure construction, by rights, people have equipped the management organization with specific purposes and functions. This means the organization represents the subjects' prescription of the original force system. Initially, people paid far more attention to the choice of organizational subjects, the design of the organizational structure and the arrangement of the organizational functions, all of which are the other organizations to the management organization. In fact, regarding the complex forms of force systems, the subjects within the organization spontaneously establish new organizational behaviors and functions beyond the expectations, a result known as the self-organization of the management organization. Taken together, the overall behaviors and functions of the management organization in mega infrastructure construction constitute the aggregated results of the other organization and self-organization, i.e., the emergence of the overall behavior of the management organization on a macro level (Robertson 2003; Gavetti 2005).

Emergence cannot be achieved by the simple sum of the micro subjective force systems in the macro behaviors and functions of the management organization.

The theoretical perspectives regarding the emergence of the management organization's overall behavior in mega infrastructure construction are as follows:

1. Emergence is represented by the behavior and phenomena of the management organization on a whole and at the macro level. As such, it should have a renewed sense of the whole and the macro level of the organization, and it should embrace new concepts. However, these behaviors and phenomena do not exist at the micro level of the subjects. That is, there is a fault, or fissure, between the macro emergence and the micro individual force system.
2. The occurrence of the emergent phenomena of the organization generally requires no new subjects in the organization because the subjects' attributes with respect to the force system have changed, some new ways of relating to the force system have occurred, and the two cases have appeared simultaneously. In this way, some changes in the macro structure of the management organization or changes in the behaviors of the subjects may have occurred that led to changes in the behaviors of most of the subjects in the organization. Accordingly, the series of self-organizing behaviors among subjects may have gradually magnified or evolved into a series of much more unexpected overall behaviors and functions under the effect of the meso operating mechanism in the organization, a situation that would result in the emergence of the management organization.

3. The emergent phenomena of the organization appear during the dynamic course of organization. The complex form of the subjects' force system at this stage differs from not only that of the last stage but also that of the next stage. Whether it be the force system of a single subject or the force systems of multiple subjects, there may occur new and unexpected dynamic phenomena in the next stage. These phenomena may have blocked some of the intrinsic relevance among subjects, or they may have produced certain new relevances. Regardless, using the formation process of the overall behaviors and functions of the management organization in mega infrastructure construction, there is a series of complex and profound changes either in the subjects' own force systems or in the direct manifestations of the relationships among subjects' force systems.
4. These cases have made it impossible for people to accurately predict the formation path of emergence. Thus, though the emergent phenomenon is generally unpredictable at first, the subsequent observation of the emergent phenomenon, i.e., why and how it occurs, can be explained, which means that after observing the emergent phenomenon, under the framework of the macro cognitive concept, it can be explained based on its relevance to the various types of the micro subjects' force systems, but it cannot be deduced in advance by the interrelations among the subjects' force systems in advance. In particular, on a macro level, we can introduce some new ideas and concepts to explain the phenomena. For example, the different force systems of the organization's subjects share phenomena similar to that of macro organizational behavior, which can be explained by the effect of the organization's external environment, the accidental factors that occur during the organizational dynamic process and the critical conditions for the occurrence of the organizational behavior.

Thus, to realize and analyze scientific problems in the management organization of mega infrastructure construction, it is necessary to consider the technical route of the complex forms of the subjects' force systems of the management organization on a micro level, that is, the interaction and evolution of force systems among subjects on a meso level, and the emergence of overall complex behavior and functions on a macro level.

7.1.6 Dynamic Analysis of Collusive Behavior in the Management Organization of Mega Infrastructure Construction

By employing concepts such as force systems and complex forms of management organization in mega infrastructure construction, we can study not only the general behaviors of the organization but also the special behaviors of the organization formed under certain conditions, such as collusive behavior, which is common in the construction management organization (Le and Shan 2013).

Collusion is a common phenomenon in social, political, and economic activities. The second edition of the *Oxford English Dictionary* defines collusion as "a secret agreement reached by two or more groups in order to undermine the interests of third parties or with no purposes." With respect to economics, collusion refers to the behavior of multiple agents who possess superior information to reach an agreement that will improve their own utility when the master agreement between the principal and the agent is incomplete (Chotibhongs and Arditi 2012; Zarkada-Fraser 2000; Le et al. 2013).

During the course of establishing mega infrastructure construction, when the construction subject possesses superior information and power, whether the subject be the government, owner, contractor, or supervisor, and uses the asymmetric information, system deficiency, and supervision loopholes aligned with other subjects to benefit in an illegal way, such behavior is referred to as collusive behavior. In Chinese, "合" means that two or more subjects coordinate with each other to do or engage in a certain type of work. Although "谋" originally refers to planning, here it means conspiracy (Zarkada-Fraser 2000). Therefore, collusion is the act of conspiring on an illegal event. In the process of establishing mega infrastructure construction, there exist various types of collusive behaviors. For instance, in the bidding stages, behaviors such as together-conspired bidding and collusion bidding cause suitable bidders to lose in the bidding processor raise the construction price, which seriously damages the interests of project investors. Thus, it is important to establish a mechanism to governor prevent collusion in mega infrastructure construction. Accordingly, the foundation of this study is based on clarifying the occurrence mechanism and the evolution path of collusive behaviors, which requires us to think about and analyze such behaviors from the perspective of the force systems of the subjects.

Collusive behaviors are classified into two types. The first is collusion on the individual micro level within the construction management organization, that is, collusive behavior of two or more persons in the organization to obtain illegal financial gain. The second type is collusive behavior among organizations.

However, according to the hierarchical structure of the principal-agent relation, there are other classifications of collusive behaviors. For example, vertical collusion occurs between the agent and the principal or between the agent and the supervisor and is manifested as the abnormal cooperation between the principal with no information priority and the agent with information priority or between the agent with no information priority and the principal with information priority (Nordin et al. 2011). This type of collusive behavior demonstrates the collusion between two subjects from different levels in the principal-agent relation. For example, regarding collusion between the government and the contractor, the contractor bypasses the project manager and conspires with the government. More specifically, the government officials may exploit their administrative power to force the project manager to award the project contract to the contractor. There is also lateral collusion, which is collusion between fellow agents that manifests as a possible collusive alliance between agents with different functions.

To reveal the inner formation mechanism of collusive behaviors, the inner and external evolutions and the evolution path of collusive behaviors from the perspective of the organizational force system must be analyzed.

Then, the primary parties involved in the management organization of mega infrastructure construction are used as examples to analyze the dynamic structure and evolution path of collusive behaviors.

1. Government: Construction Management Agency (Fig. 7.3)

In this text, the agent-construction system is used to analyze the evolution of and relationship between the power and behaviors of the government and the construction management agency.

In the general agent-construction system, the government authorizes the agency, which has extensive construction management experience, to act as the agent responsible for the bidding activities. This results in the joining of the contractual power and the legal economic power. Thus, through economic and contractual powers, the construction management agency gains financial interests as a result of its own construction management ability, and it realizes the engineering resource allocation and integration through economic power. Moreover, the government, perceiving its administrative power as a bond, executes public affairs management power with respect to decision-making and management, and it regularizes subject behavior through legal power under relevant engineering laws and forces in mega infrastructure construction.

However, if the law and the relevant systems are defective or the prevention and supervision mechanisms are incomplete and the related government organs realize the loophole, for the pursuit of political achievement, they may enlarge the influence of administrative power on the construction management agency from top to bottom. They may even transfer profits to the construction management agency and then collude with the agency by intervening in the project feasibility analysis to increase the possibilities of future projects (Dorée 2004). This is indicative of political collusive behavior within the management organization that is governed by power from top to bottom.

In addition, by taking advantage of an unsound legal environment, incomplete contracts, and the lag in the transference of information, the construction management agency may transfer profits to government officials who wield decision-making and approval powers and may even halt the tunneling until the government officials succumb to the lure of the profits and agree to enter into an alliance. Because the original existing and extremely important legal power and the constraining force may be weak or even disappear, the collusive behavior between the parties emerges, resulting in various illegal financial benefits from the government.

2. Contractor: Construction Management Agency (Fig. 7.4)

The agent-construction system is used to analyze the evolution of the force system and the behaviors between the construction management agency and the contractor.

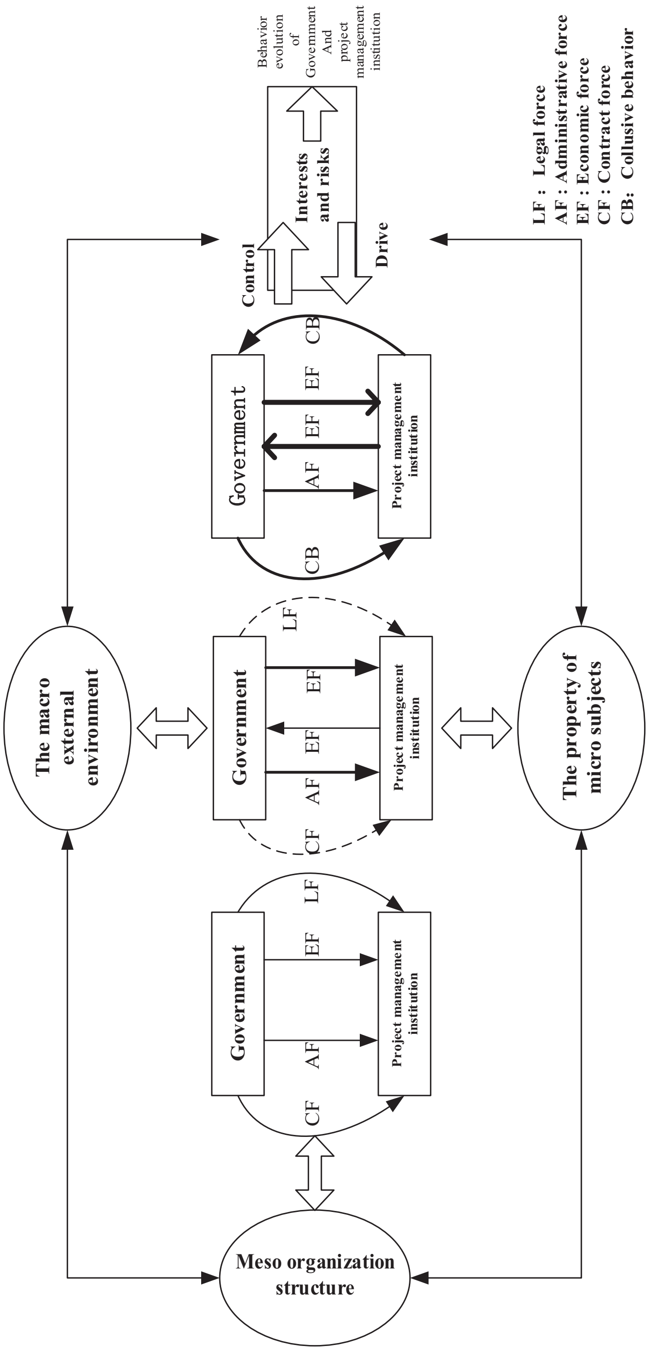

Fig. 7.3 The evolution of the force system of government-construction management organization

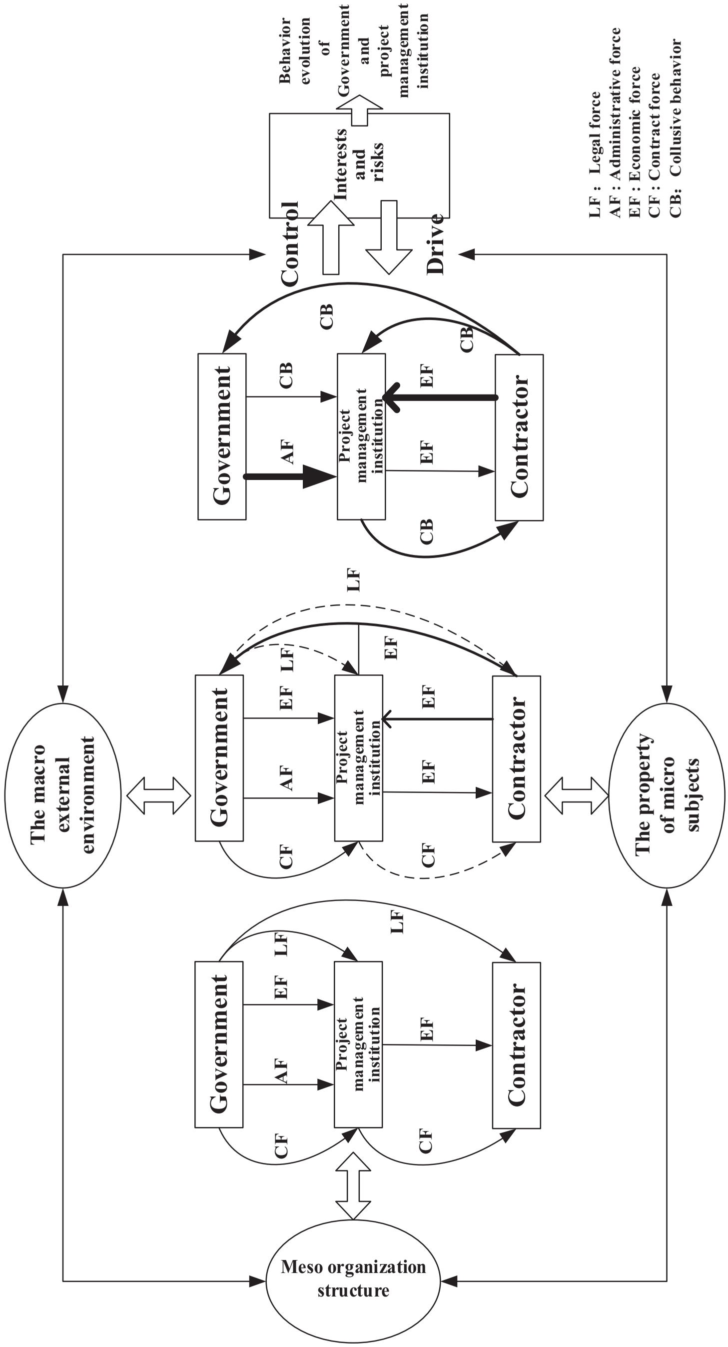

Fig. 7.4 The evolution of the structure of the force system in the construction management organization

In the agent-construction system, the construction management agency engages in contractual agreements with the contractor through its contractual power under the condition of an open market and pays for the contract, thus creating economic force. The contractor is supposed to accept the supervision of the relevant law of engineering construction through the legal power grated under the legal system of the country.

The contractor, however, represents the enterprise that is in pursuit of profits under liberation, and as such, it hopes to maximize its profits. Those enterprises that exploit information priority may chance transferring economic profits to the construction management agency thinking that the law will not punish the majority of people who commit the same mistake. Thus, the constraints and supervision of the legal environment as enforced on the construction management agency are weakened. Consequently, the collusive behavior between the contractor and the construction management agency emerges. For example, at this point, the construction management agency may deliver the contract to the collusive contractor and receive kickbacks by using its administrative power, while the contractor is awarded the engineering contract through the cohesion of the economic power that would not otherwise have existed (Lo et al. 2007).

Some contractors may even directly transfer profits to the government or the government officials who wield the powers of decision-making and approval, and the government officials then exert their power to force the construction management agencies to award the contracts to the contractors by strengthening the administrative power. At this time, both the legal power and the contractual power are corroded by the administrative power and economic power, leading to variations in or even the loss of each subject's functions as stipulated in the contract. The collusive behavior that now arises from the organizational structure is allocated by power from top to bottom, which weakens the contractual power to acquire illegal profits due to the strengthening of the administrative power.

These situations all belong to the category of vertical collusive behavior in that vertical collusive behaviors are often derived from a superincumbent strong central authority or from information asymmetry in a multilayered organizational structure, whereas lateral collusive behaviors often occur among equative agents. The reason for this lies in their common interests. Therefore, the economic power is the result of two parties who originally had no relation with respect to force. Since the change in the force system is quite simple, we do not focus on lateral collusive behaviors.

According to the analyses, rather than being static and changeless, the comprehensive form of each subject's force in the management organization of mega infrastructure construction changes with changes in the macro environment, organizational structure, and attributes of the micro subjects. Furthermore, the behaviors of the management organization are not merely composed of several factors and contact points, but they instead originate from the constant evolution, emergence, and self-organization of the inner force system. Thus, the dynamic analysis confirms the concepts presented in the first few sections of this chapter.

Overall, the core driving factor for the formation of collusive behaviors is that the interests, both economic and political, are greater than the risks, which suggests that the fundamental element of collusive behaviors lies in constraining the economic and administrative powers within a reasonable scope and strengthening the constraints and disciplinary functions of the legal and contractual powers.

7.1.7 Dynamic Analysis of Decision-Making in Mega Infrastructure Construction

The dynamic concept and theory of organization mode in mega infrastructure construction have been discussed in a general sense in the previous sections of this chapter. Thus, we analyze the structure of the dynamic force system and the dynamic principle of the project, focusing on a specific organization, such as decision-making and construction organizations in management construction. The uniqueness of the organization can result in more concentrated and detailed analyses.

The organizational mode of decision-making with respect to the construction of the HK-Zhuhai-Macao Bridge in China is used to analyze the dynamic principle.

1. An Introduction to Organizational Decision-Making Regarding China's HK-Zhuhai-Macao Bridge

China's HK-Zhuhai-Macao Bridge was a large-scale transportation infrastructure project in which the governments of Hong Kong, Guangdong Province, and Macao, under the dominance of the central government, invested. Since the project involved three districts and a special scenario that involved legal, administrative, and economic environments as well as parliamentary procedures for making decisions under the one country, two systems policy of China, which required the government of the three districts together with the related state departments to be the subjects, involved in the decision-making process. In this way, the organizational mode of decision-making with respect to the HK-Zhuhai-Macao Bridge was formed.

Furthermore, guaranteeing the scientific and proper schemes of decision-making in complex decision-making problems requires multiple disciplines and experts in various areas to form a decision-making supporting platform to aid those actually making the decisions.

Accordingly, the decision-making problems of the HK-Zhuhai-Macao Bridge project involved many areas at many levels and scales. Thus, to improve the ability and efficiency of the decision-making process, it is necessary to consider decision-making problems that exhibit different properties as the guide and to construct a corresponding organizational mode of decision-making with little redundancy and high efficiency. In this way, during the process of making decisions, a dynamic evolutionary organizational mode of decision-making should emerge rather than a consolidated rigid one.

The following three aspects constitute the basic principles for the design of the decision-making mode of the HK-Zhuhai-Macao Bridge.

2. Analysis of the Basic Force System of Organizational Decision-Making in the HK-Zhuhai-Macao Bridge Project

The subjects responsible for making decisions regarding the construction of the bridge must possess corresponding public power and, on this basis, establish necessary routine power in the decision-making process. To a great extent, the relationship between the decision-making subjects and the decision-making support platform is directly or indirectly entrusted and maintained through public power.

The organizational mode of the decision-making with respect to the HK-Zhuhai-Macao Bridge project is broadly separated into four stages (Jin et al. 2013).

In the first stage, the primary tasks are to conduct a comprehensive assessment of the significance and necessity of the construction of the bridge on the macro levels, such as politics, society, and economy, and to ensure whether it is necessary to conduct a feasibility study regarding this project. The administrative power and the routine power responsible for completing this decision-making task are concentrated within the central government, whereas the support for the decisions must be to be provided by the administrative power of the three governments. To conduct a comprehensive assessment of the decision-making process and maintain impartiality, the central government can directly entrust authoritative professional departments to conduct the decision-making assessment. Therefore, in this stage, entrusted by the public, the government, as the main subject of the decision-making body, is supposed to construct the organizational decision-making mode with corresponding routine power through either the direct or indirect transfer of public power. To guarantee the development of decision-making, even if there were a few economic contract relations between government agencies and professional institutes, when compared with the efficiency of the strong administrative force system within the entire organization, the efficiency of this economic power is insignificant. Furthermore, the property of the professional institute engaged in the decision-making task has determined that its primary behavior is not equal to the enterprise market behavior under the environment of a market economy.

Thus, in this stage, the main elements of the force system between the subjects of the decision-making body form the inner force system (Fig. 7.5a) of the decision-making organization.

During the execution, the central government appoints the national macroeconomic planning and management department (National Development and Reform Commission) to take over the decision-making responsibilities on behalf of itself. Thus, a chart of the structure of the force system in the decision-making organization is presented in Fig. 7.5b.

The second stage followed the decision-making achievement attained in the first stage. Thus, the primary decision-making task in the second stage was each subject's supportive argument on the engineering feasibility analysis, such as the traffic volume survey and analysis, the contents of the project and its major technical standards, construction conditions, bridge location, project construction schemes, port and facility layout, and environmental impact assessment, and the feasibility study with respect to decision-making problems, such as financing schemes. Because the decentralized decision problems were directly related to the political, social, and economic statuses in Guangdong Province, Hong Kong, and Macao, the decision preferences of the three districts consisted of both similarities and differences, a situation that caused conflicts of interests. Therefore, on the one hand, the governments of the three districts played direct and important roles in the organization of the decision-making body at this stage. On the other hand, the conflicts among the subjects within the organization increased. Because the three governments share the same administrative status, a special agency to coordinate the

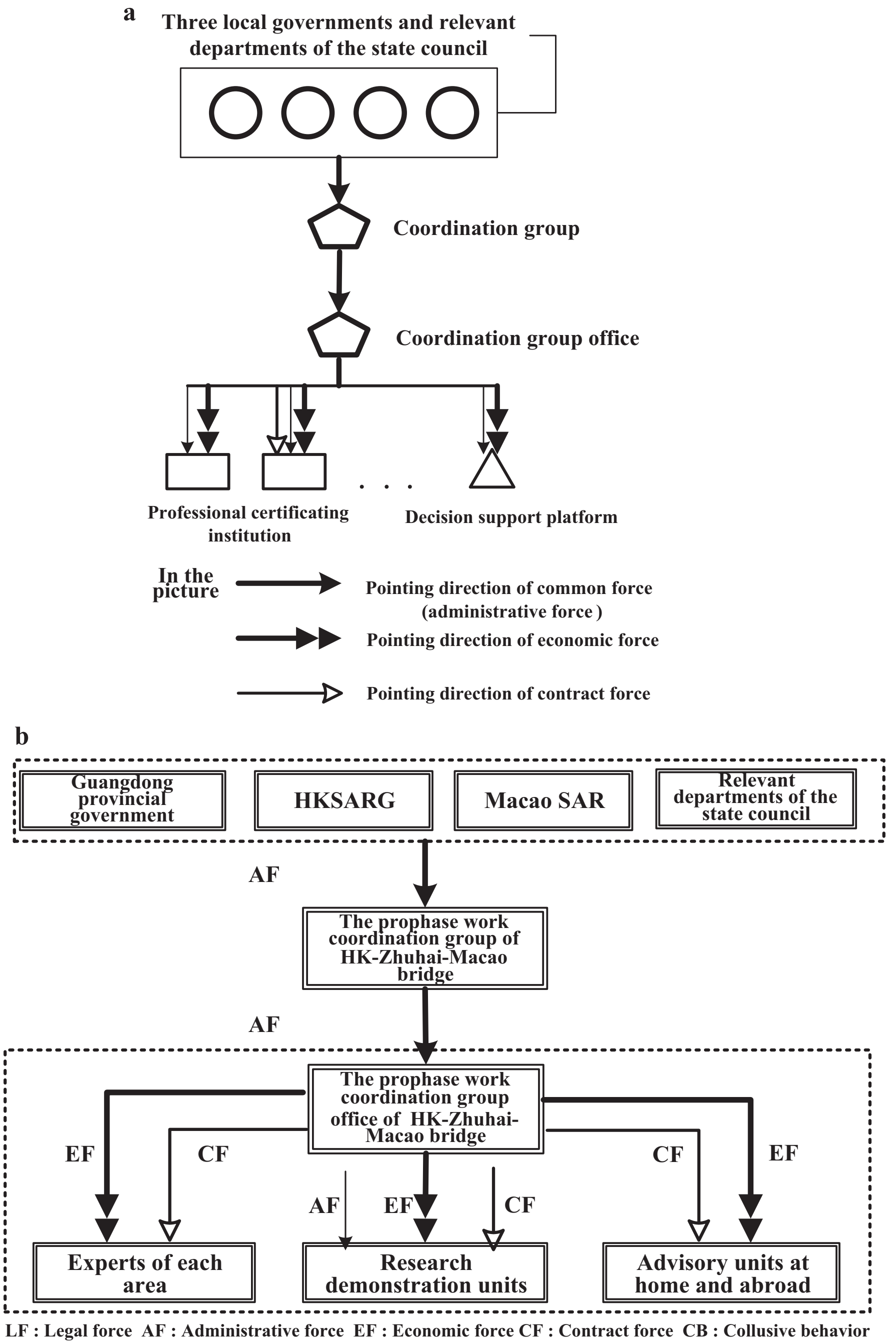

Fig. 7.5 (**a**) The inner force system graph of decision-making organization in the first stage. (**b**) The structure chart of force system of decision-making organization in the first stage

administrative power of the three governments was to be established during this stage. That is, the preliminary work of this agency was to coordinate the construction of the HK-Zhuhai-Macao Bridge project, and as such, its specific executive power was delivered to the permanent organ under its umbrella (the coordinate office), and its working principles and procedures were stipulated.

Additionally, during this construction feasibility stage, it was necessary to demonstrate numerous specialized decision schemes, hence the need for a professional demonstration team. The decision schemes are demonstrated by authoritative and independent institutions that possess legal entity status and are selected through the market bidding process. Accordingly, the duties and obligations of the two parties are ensured by both economic and contractual powers. Meanwhile, the legal power established a normal environment for the two parties. A chart of the inner force system of the decision-making organization is presented in Fig. 7.6a, and the structure of the force system of the decision-making organization is presented in Fig. 7.6b.

Therefore, the decision-making during this stage is a function of administrative and economic powers. The administrative power ensures the authority of the routine power of decisions, especially for the group that effectively ensures the synergistic effect of the public power of the decision-making subject in various domains and moderates and resolves the conflict of forces. On this basis, using legal power has not only helped to establish an efficient decision-making support platform, but it has also created the opportunity to for establish a competent feasibility argumentation institute. At this moment, as a social and independent professional corporate body, the economic power transforms from the administrative power, and the HK-Zhuhai-Macao Bridge coordination group serves as the bond that links their duties and obligations, an operation that is guaranteed by the stipulations of the legal and routine powers. Meanwhile, the contractual relationship and legal relationship intensify the duties of the professional corporate body and ensure the high quality of the decision-making scheme.

The third stage advanced the progress of the construction feasibility argumentation, as the basic decision-making scheme of the construction project had the approval of the three districts. However, the complexity of the decision-making problems, such as the proportion of contributions of the three governments, the jurisdiction of the port mode, and the ecological compensation for protecting the Chinese white dolphins, was becoming increasingly more evident. The HK-Zhuhai-Macao Bridge was a cross-border project, and the governments of the three districts were the subjects of the project's establishment and investments. Nonetheless, with respect to the important problems that required decisions by the three governments, such as the mode of project approval, the investments, and the port, there existed different administrative management principles and procedures. Thus, it was inevitable that the differences would increase many of their connections as well as the communication and coordination links among the three bodies. More specifically, the administrative powers of Hong Kong and Macao are highly autonomous and independent, and as such, the three districts had to fully communicate with each other and be flexible to reach consensus on decisions. For example, selecting the

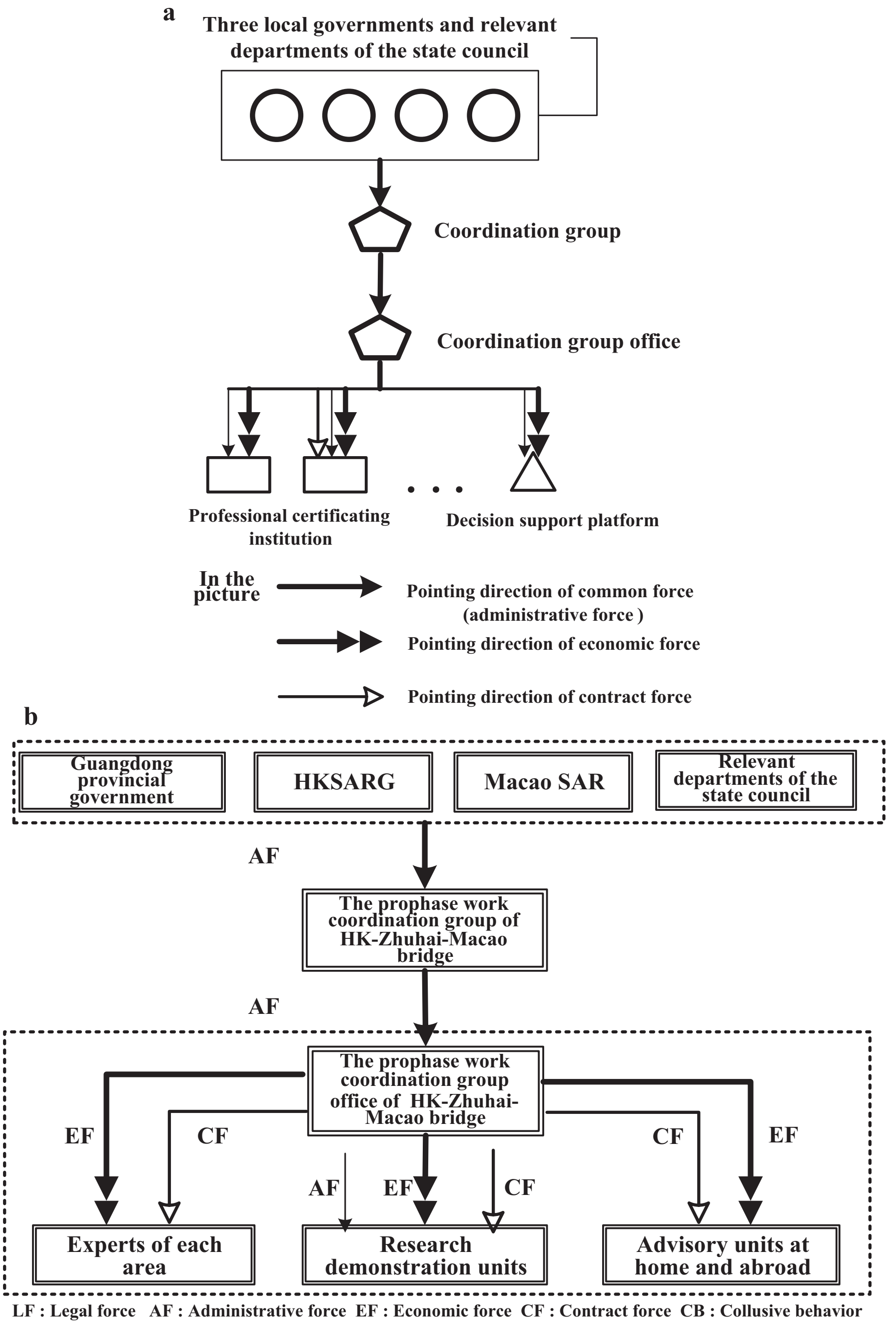

Fig. 7.6 (**a**) Chart of the inner force system of the decision-making organization system during the second stage. (**b**) Graph of the structure of the force of the decision-making organization during the second stage

port mode of the HK-Zhuhai-Macao Bridge was required to fully consider certain legal issues that resulted from the various issues related to the port layout, such as the jurisdiction and the relinquishing of some bridge surfaces. In the decision to protect the Chinese white dolphins, conflicts arose between the protection of the dolphins and the location of the bridge location, creating a problem during the decision-making stage. Faced with these complex problems and the increased difficulties with coordination, the administrative force systems of the three districts created an administrative force that was well organized and efficient and was able to arbitrate the nonisotropic force of the three districts according to their nonisotropic properties and the deficiencies in the authority of local governments' administrative powers. According to this principle and based on the three governments, a higher-level authoritative institution was established, namely, the task force of decision-making. Led by the National Development and Reform Commission and comprised of the Department of Transportation, the Hong Kong and Macao state council offices, the Guangdong provincial government, the government of the Hong Kong Special Administrative Region, and the government of the Macao Special Administrative Region, the HongKong-Zhuhai-Macao Bridge task force, which was responsible for policy coordination and supervision, oversaw the decision proposals regarding the project's upfront work submitted by the coordinating group and the problems related to decisions as well as other problems as assigned by the central government. Furthermore, the task force had to manage major problems involving the central power and the controversy and conflicts that erupted among the three districts during the project's preliminary work.

Therefore, coordinating the specific problems through the administrative power of the task force when the routine power exceeded that of the administrative power of the three governments or when the three governmental bodies could not reach consensus actually reinforced the administrative power of the central government to make decisions regarding the HongKong-Zhuhai-Macao Bridge project. Moreover, the efficiency of the decision-making improved because the decision-making capability of the force system within the organization was inadequate and could not address the new problems that were emerging. Thus, the force system within the organization changed, as presented in Fig. 7.7a. The actual force system of the organization with respect to decision-making in the third stage is presented in Fig. 7.7b.

During this stage, the new administrative force of the task force strengthened the authority of the routine power to make decisions regarding many complex issues, particularly the coordination of the legal power and the administrative power of the three governments under the system of one country, two systems, and further improved the inner force system's coordination mechanism of the original organization's decision-making process.

As an example, we consider the decision of the port mode, which directly transcended the jurisdiction of the administrative power of the three governments. The task force, with the central government directly involved in the process, was able to ensure that the problem could be resolved at the administrative and legal levels. As another example, the protection of the Chinese white dolphin involved conflicts between the bridge project and the protection of the dolphins that were directly

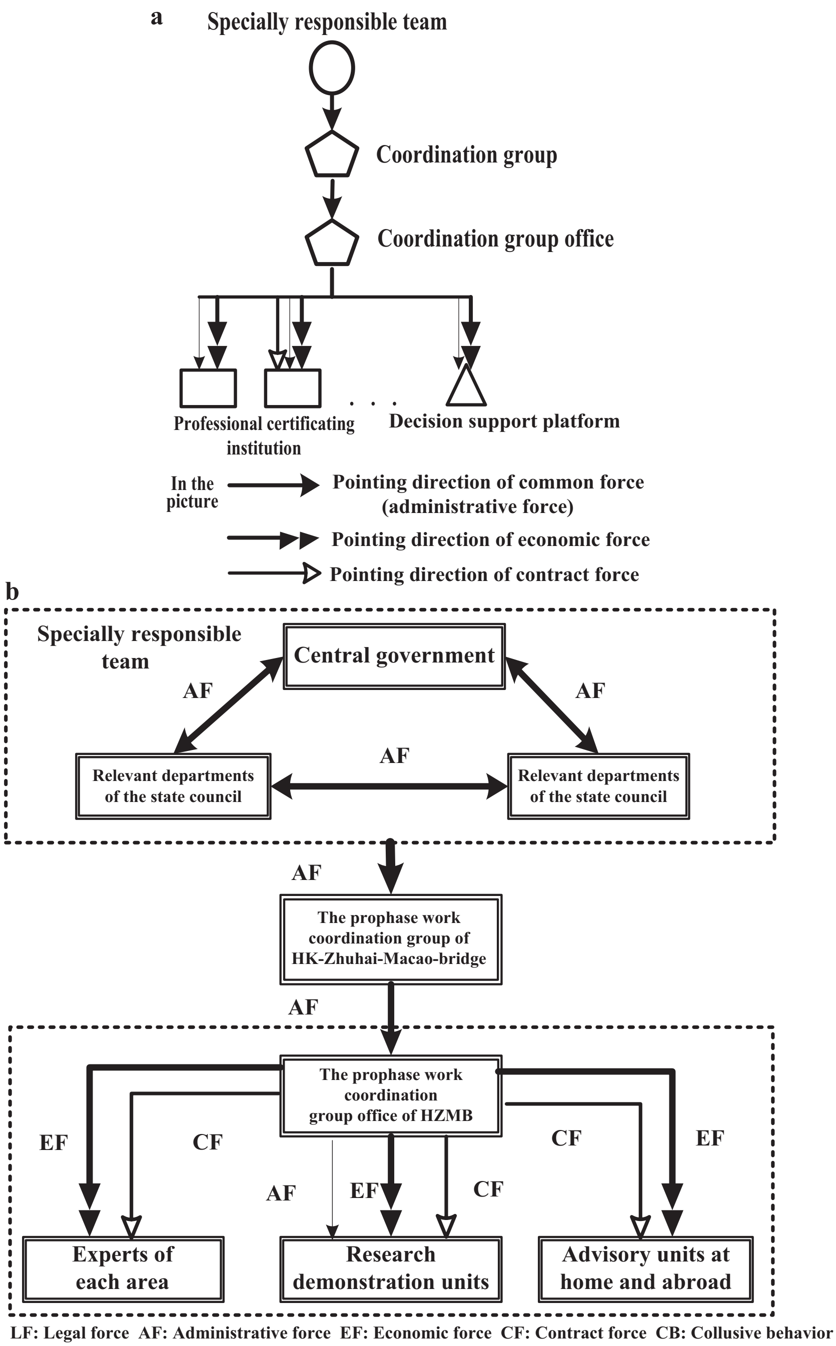

Fig. 7.7 (**a**) The inner force system of decision-making organization in the third stage. (**b**) The structure of the force system of decision-making in the third stage

related to whether the cultural power of mega infrastructure construction could embody the social responsibilities of such complex projects. Nature and the principle of protecting the environment should be fully respected under strict administrative and legal powers. The comprehensive adherence to the law can be accomplished by establishing equilibrium between the legal powers of project engineering and the cultural powers of environmental protection and compensating functions. Thus, in this stage, establishing a task force helped to replenish the administrative power and reinforce the legal and cultural powers. Furthermore, the original inner force system of the organization with respect to decision-making was adjusted such that the overall decision-making power was ineffective, and the functions of the decision-making organization could have been better orchestrated.

The fourth stage, which followed the completion of the feasibility study of the HK-Zhuhai-Macao Bridge project, focused on the coordination of the decision-making with respect to the construction project. Decision-making problems often manifest as stable and normal site decision-making problems. Thus, the priority at this stage is to maintain the stability and the executive force of the decision-making ability. Hence, it is necessary to employ the simplest and most unhindered organizational structure and mode as well as a relatively short decision-making path to improve decision efficiency.

Accordingly, a permanent functional institution was established on the premise of retaining the task force, the committee, and the coordinating group of the three districts. This institution was entrusted by the three districts and endowed with corresponding decision-making powers. Furthermore, the function disposition of the institution as well as the flexible management mechanism was conducive to the achievement of related decision management tasks. When abnormal or sudden decisions were made, they could also temporarily address related issues. This practice was named after the Hong Kong-Zhuhai-Macao Bridge Management Authority. Specifically, because the original focus of the organizational decision-making power was transferred below the authoritative level, the executive force could more quickly manage site decision problems.

The inner force system of the decision-making organization is presented in Fig. 7.8a and that of the actual execution is presented in Fig. 7.8b.

With respect to large-scale major projects such as the HK-Zhuhai-Macao Bridge, in the engineering coordination stage, the core force of the inner force system of the decision-making organization was still the administrative force because, for several reasons, it was necessary to exploit the superiority of the administrative force. For example, because regional differences remained during the construction of the HK-Zhuhai-Macao Bridge, it was necessary to involve the central government, and the task force of the HK-Zhuhai-Macao Bridge was thus indispensable. Furthermore, because the three districts were independent legal and economic entities, it was fair to make decisions based on equal consultation or on the appropriate identifying characteristics of coordination according to the authority. Therefore, according to the contract assigned by the three districts, it was necessary and reasonable for the three governments to co-found the joint work committee, which was responsible for making decisions regarding major issues of the project. To do this, the committee

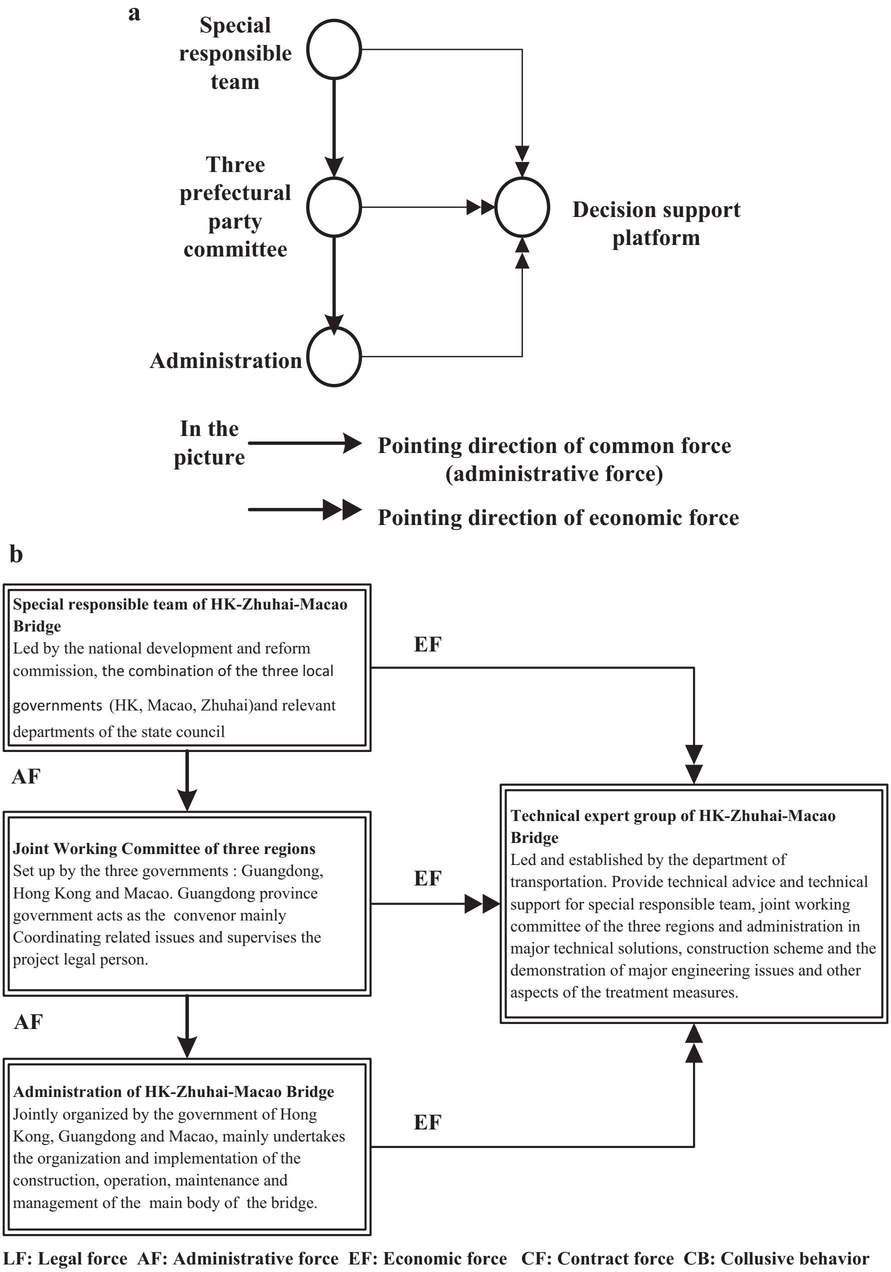

Fig. 7.8 (**a**) The inner force system of the decision-making organization in the fourth stage. (**b**) The structure of the decision-making organization in the fourth stage

adopted behaviors such as closer communications and friendly negotiations, and it acted in accordance with local legal principles, coordinated public affairs related to the project, and supervised some of the subject's project entities, including the Hong Kong-Zhuhai-Macao Bridge Management Authority. Thus, the committee of the three districts became a permanent institution that was authorized and established by the three governments through contracts and by taking charge of project preparation, construction, operation decisions, and corresponding management responsibilities. Accordingly, as provided by both the executive power of the central government and that of the three local governments, the committee held decision-making power regarding coordination decisions about the project. Additionally, having considered the supervision and control power, the property of the public project, i.e., the HK-Zhuhai-Macao Bridge, and the differences in the laws of the three districts, the three governments established, through the governmental principal-agent, a career legal subject, namely, the HK-Zhuhai-Macao Bridge Management Authority, to guide, by administrative power, the core power, which was endowed with executive power to oversee the concrete implementation of investments, construction, operations, maintenance, and management of this project. In this sense, the Hong Kong-Zhuhai-Macao Bridge Management Authority, by combining the administrative power, legal power, and economic power, realized the balance of the administration, economy, and law of the three governments. Furthermore, it has directly created a balance in the organization of the decision-making process and achieved the complete release and allocation of the power and functions of the organization with respect to decision-making.

The flexible evolution process of the force system structure with respect to the HK-Zhuhai-Macao Bridge decision-making organization is depicted as follows (Fig. 7.9).

The HongKong-Zhuhai-Macao Bridge is a complex and important engineering system within a dynamic and open decision-making environment wherein the decision-making problems become increasingly more complex such that the aspects of decision-making is more expansive than ever before. The challenges met by those responsible for making decisions about the bridge became increasingly more serious with the gradual deepening of the construction project demonstration and the construction. To ensure that the decision-making was scientific, efficient, and timely, the HK-Zhuhai-Macao Bridge organization enacted restructuring and adaptive changes to the power system to achieve greater organizational effectiveness. From the full release of administrative power in the macro planning stage to the two-element tension of the administrative power and economic strength in the feasibility analysis stage, the central executive power is further strengthened in the conflict coordination stage, whereas the advantage and stability of administrative power are continuously acknowledged in the construction coordination stage. Accordingly, it is evidenced that the main force system of the decision-making organization in each stage is constantly evolving to strengthen the decision-making power and realize the rational correspondence between the decision-making ability and the decision-making problem to ensure that the decision-making activities are in order and effective. A detailed analysis of this evolution is presented in Table 7.3.

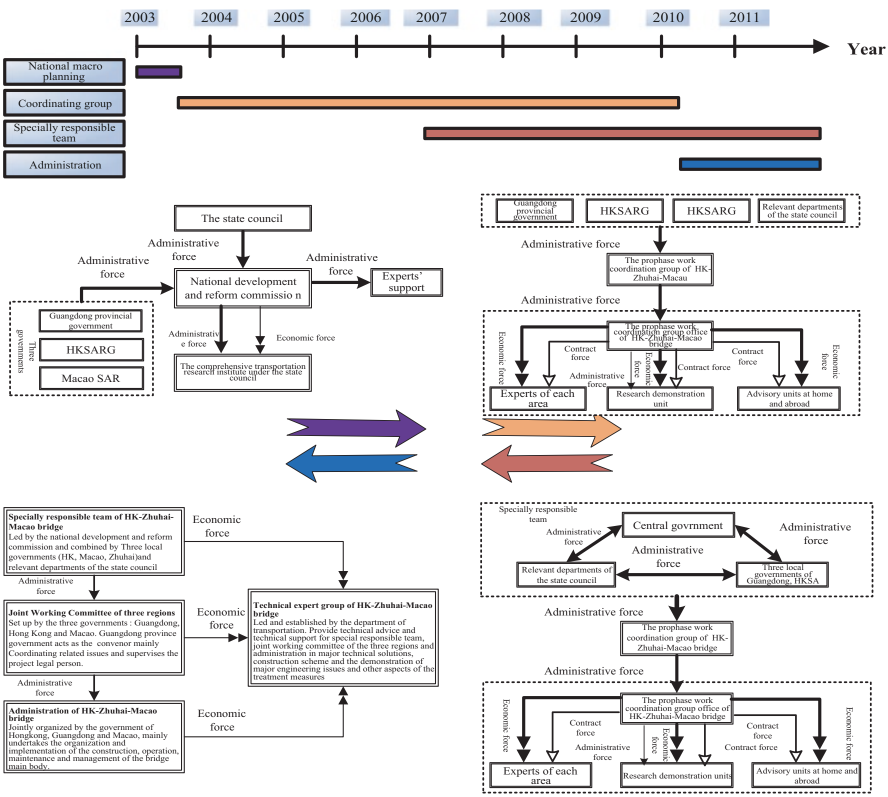

Fig. 7.9 The flexible evolution of the force system structure of the HK-Zhuhai-Macao Bridge decision-making organization

Table 7.3 leads to the proposal of certain basic rules.

1. In the process of major project decision-making, the government is the principal subject of the decision-making organization. Furthermore, it is lawful and reasonable to use administrative power to examine the important issues of major projects, and the effect of doing so is irreplaceable. The government's political status, representation, authority, and ability to integrate resources into the decision-making process are incomparable to those of any other social organization or individual. Therefore, in the decision-making organization, the administrative power is the dominant core force.

   The government, as a representative of the social public interests and as an investor in project, makes important choices and decisions regarding the types of public products that are to be provided to certain projects, whether they should be provided and when they should be provided. This is the social responsibility of the government when entrusted with making major engineering decisions. To fulfill this responsibility, the government has decision-making power, but it also

Table 7.3 Analysis of the evolution of the structure of the force system during the decision stage of the Hong Kong-Zhuhai-Macao Bridge

Decision-making stage Analysis items	National macro planning stage	Three government coordination decision-making stage	Central government coordination decision-making stage	Engineering construction coordination decision-making stage
Decision problem	Comprehensive evaluation of the political, economic, and social benefits of the project	In the engineering feasibility analysis stage, the investigation and analysis of traffic volume, engineering content, technical standards, construction conditions, Scheme selection of the bridge, engineering construction project, and other basic technical solutions are considered	The port mode triggered by the jurisdiction; eco-composition problems under the constraints of Chinese white dolphin protection law; the uncoordinated investment and financing modes in the three district system	The decision problem maintains a steady state in the engineering field
Decision subject	Central government and three government bodies jointly carry out the decision; development and reform Commission of State Council is in charge of specific affairs	The three governments are directly involved in the preparatory work, whereas the coordination group is responsible for specific decision-making, coordination, and management	The central government and the three local governments jointly establish a special team that is responsible for coordination and arbitration	The administration is responsible for the construction of the project as the main body
Decision-making power	Executive power is granted to the central government; The authority is the National Development and reform commission; The National Integrated Transport Research Institute is the ultimate executive power	Executive power: Three local government and relevant Departments of the State Council Authoritative power: Pre-work coordination group Executive power: Pre-work coordination group office	Executive power: Task force Authoritative power: Pre-work coordination group Executive power: Pre-work coordination group office	Executive power: Task force Authoritative power: Three governments agencies that form a working committee Executive authority: Authority

Organization power	Administrative power is nuclear power; legal power is restrictive and guaranteed	The two-element tension function of administrative power and economic power; economic power maintenance of contractual relationship; Contractual force that strengthens the function arrangement; Legal power that provided restrictions and guarantees	The strengthening of the administrative power of the central government	The structure of the power system is simple and clear; it can exert the advantage of administrative power

has the ability and authority to analyze and assessment he overall benefits, functions, risks, and costs of the project. In other words, the government possesses the necessary decision-making power. The timely evolution of the Hong Kong-Zhuhai-Macao Bridge decision-making organization following the changes in decision issues corresponds to the matching and docking among the key decision resource factors, such as power, function, ability and support of the decision organization, and the emergence of the complex decision problems to be solved. The necessary powers and abilities to manage and resolve the different decision-making problems are not all the same. Therefore, to avoid the phenomena known as power redundancy and lack of power, only flexible decisions by the organization and the organization system of force throughout the continuous evolution of the project that are compatible with and relevant to the problem can improve the quality and efficiency of the decision-making process.

2. Although administrative power is the core of the decision-making organization, this power can vary with respect to both size and level. The various levels of administrative power are based on different power attributes necessary for the specific decision-making problem. Therefore, the corresponding relationship between the decision problem and the level of government should be clear when making decisions. Otherwise, if the level of power is too high, which is a type of top-down (offside) power, it will cause redundancy. If the level is too low, which is a type of bottom-up (offside) power, it may result in a lack of authority and maneuverability. In the event that there is a failure to establish the appropriate correspondence between the proposed decision problem and the applicable level of government, it results in a power blind area or in the absence of government administrative power at the government level. Therefore, in the process of major project decision-making, the decision organization must ensure that one does not exceed one's power or authority and that there be no absence of power when making decisions. Thus, it is necessary to establish a hierarchical coordinated decision-making mechanism according to the power, the importance, and the correlation of the decision-making issue and to determine the responsibilities for all powers at all levels of government according to the size of the common power and coordinate the indispensable and irreplaceable roles of all levels of government.
3. In the process of decision-making, power conflicts will inevitably arise, and it is generally the responsibility of higher levels of administrative power to resolve the conflict. Using the legal conflict of the Hong Kong-Zhuhai-Macao Bridge as an example, the three legal systems of Hong Kong, Zhuhai, and Macao have different administrative rules and procedures. The decision-making process involves many legal issues, a situation that may become problematic when the decision-making activities are subject to the different legal systems and administrative regulations of the three governments, causing conflict among the legal force of the three governments. There are occasions when, given the three layers of government, the administrative power cannot resolve the conflict due to a lack of decision-making power. When this occurs, it is necessary for the central government to intervene to ensure the accurate operation of the legal force and to balance the internal force system of the decision-making organization. Thus, in

the decision-making process, under the constraint of legal force, the three governments should fully respect the territorial law and make full use of the administrative powers' complementary policies and conditions to fill in the gaps in the laws and regulations of the three governments.

7.2 Decision-Making Given Deep Uncertainty in Mega Infrastructure Construction

Herbert A. Simon said, "Management is decision-making." The premise of this statement also applies to mega infrastructure construction management. This means that, although the content and form of mega infrastructure construction management activities are many and varied, the most common and important behavior of management subjects involves decision-making activities.

Generally, the decision-making activities of mega infrastructure construction management can be divided into different levels. When considering only decision-making problems, there are, generally, three levels.

The first level of decision-making problems, which is prevalent at the basic level of mega infrastructure construction management, is characterized by both conventional and repetitive features. This level of decision-making problems involves relatively few elements where the degree of certainty of these elements is high and the input/output relationship is clear. Accordingly, the decision-making subject can complete the decision-making task according to the specified processes and rules. As such, this level of decision-making problems is rule based, procedural, and, most often, structured.

The second level usually appears at the mid-level of mega infrastructure construction management, such as problems related to the division of construction tenders. An example of such a decision-making problem is one that simultaneously involves many elements, such as construction schedules, quality, and risks, and includes various uncertainties. This level of decision-making problems involves an increase in the elements with close relationships. Furthermore, uncertainty in this level of problems is enhanced. Whereas some of these decision-making problems can be managed through structured models, others, primarily semi-structured decision-making problems, can be resolved by using nonstructural models, such as deduction, analogy, and comparison.

The third level of decision-making problems, which are most often unstructured decision-making problems, often appears at the macro level of mega infrastructure construction management, such as engineering feasibility studies, assessments of social and economic benefits, and investment and financing mode selections. This level of decision-making problems involves many factors, including a complex relationship between factors, a decision-making target that is difficult to clarify, and a severe degree of uncertainty. These characteristics fully reflect the complexity and integrity of the problems in mega infrastructure construction management.

With respect to the three levels of decision-making problems, the first and second levels are relatively easy to resolve, the solution is relatively mature, and the decision-making subject generally possesses the appropriate decision-making capabilities. With respect to the third level, however, due to its complexity, it is difficult to the mega infrastructure construction decision-making activities. Moreover, to resolve this level of decision-making problems, it is necessary to identify new cognitions, design new methods, and research new scientific problems.

7.2.1 The Fundamental Discourse in Mega Infrastructure Construction

To reflect the features of the complexity of the mega infrastructure construction decision-making activities, the focus of the research is the third-level decision-making problem. With respect to the first- and second-level decision-making problems, they are separated from the third-level decision-making problems because the nature and method of the lower-level problems are consistent with the decision-making problems of general construction. In other words, the decision-making problem of mega infrastructure construction in this book refers to a class of complex decision-making problems in mega infrastructure construction management.

Three types of practical problems belong to the typical complex decision-making problems in mega infrastructure construction management.

The first is a fundamentally decisive decision-making problem that is specifically related to construction. This type of decision-making problems generally influences the function, quality, and construction operations of the mega infrastructure construction entity, such as the construction location and design. The complexity of this type of decision-making problems is reflected by the following: first, almost all of the important elements and the entire process of the construction; second, the decision-making problems are more concentrated in the initial stage of the construction. At this point, the information needed to resolve the problem is incomplete, and the subject's ability is not sufficient. Third, the decision-making results have a significant effect and are highly sensitive to the subsequent construction and operations of the project.

The second is a decision-making problem that occurs during construction and requires innovative problem solving.

This type of decision-making problem is often associated with problems involving the natural environment and technical issues that are difficult to predict, such as specific technology requirements and selection of the design of the major construction scheme. Both of these problems can be solved through innovation. The complexity of this type of decision-making problems reflected through the following characteristics: first, the decision-making subject does not possess the requisite thorough knowledge or ability to engage successfully in the decision-making process; and second, the decision-making subject needs to build an innovative platform to achieve innovative goals, an action that, by itself, leads to a series of new and complex decision-making problems.

The third type is the developmental strategic decision-making problem that occurs during construction.

This type of decision-making problem possesses obvious macro, strategic, and global significance, an example of which is the design of the overall function of mega infrastructure construction. The complexity of this type of decision-making problem is reflected in the following: first, the goal of the decision-making has multi-level, multidimensional, and multi-scaled features; second, the deep uncertainties between the decision-making problem and the environment are closely related; and third, the construction value of the decision-making subjects has a substantial impact on the decision-making.

Regardless of the type of the decision-making problem, the subjects responsible for making the decision must propose a decision scheme that includes the related issues. When considering this from perspective of a system, proposing a decision scheme is consistent with the function spectrum of a complex man-made system that is inclusive of its emergent function. This complex man-made system includes the hardware and software systems of the mega infrastructure construction. The former forms the physical functions and the key technology of the mega infrastructure construction, whereas the latter forms the management scheme of the mega infrastructure construction. In addition, the system functions are manifestations of the overall system behaviors and system attributes, which are based on correlations and structure of the factors. Thus, in the process of proposing decision-making schemes, the decision-making subjects preinstall and plan the overall behaviors and attributes of the two types of complex man-made systems through the combination of theory thinking and engineering thinking and based on both respecting the general rules and reflecting the intentions of the decision-making subjects. When decision-making subjects preinstall and plan their decisions, the values of the subjects are good; in a general sense, the decision-making subjects hope that the expected future engineering entity consist of well-developed and well-designed functions. However, because of the complexities of the mega infrastructure construction itself and the mega infrastructure construction-environment compound system, not all of these positive attributes are to be achieved on schedule. Moreover, some unexpected and unplanned negative functions may emerge. This scenario reflects the complexity of the decision-making target design of mega infrastructure construction.

There is a logical relationship with respect to complexity thinking that must be clarified. Any system attributes cannot exist apart from the entity. Thus, in proposing a decision-making scheme, some of the system attributes are theoretically set at the level of insubstantial engineering by the decision-making subjects, preinstalled according to the subjects' assumptions and idealized conditions, and those system attributes are divorced from the entity. Nonetheless, the function value and effect of the decision-making scheme must be reflected and implemented through the construction entity and management activities. This suggests that the process of design, formation, and implementation of the mega infrastructure construction decision-making scheme is the combination of theory thinking and engineering thinking, and moreover, it is generally transformed from theory thinking to engineering thinking. Accordingly, this transformation not only embodies path dependence, but it is also full of uncertainty and characteristics of evolution, and as such, it represents a major manifestation of the complexity of the mega infrastructure construction decision-making process and the decision-making subjects' behaviors.

Thus, it is evident that mega infrastructure construction decision-making activities are containing numerous aspects of complexity (Brady and Davies 2014; Hu et al. 2015; Giezen 2012).

7.2.2 *Decision-Making Under Deep Uncertainty in Mega Infrastructure Construction*

At the level of engineering thinking, mega infrastructure construction decision-making activities consist of a variety of specific contents and forms, whereas at the level of theory thinking, the study of mega infrastructure construction decision-making must begin with the basic attributes of the decision-making activities.

That said, however, these types of attributes can be abstracted and understood from various perspectives. For example, since the mega infrastructure construction decision-making goal has multi-scaled features, mega infrastructure construction decision-making can be perceived as a type of multi-scaled decision, and considering the iterative path of the formation of the decision scheme, mega infrastructure construction decision-making can be considered as a type of iterative decision.

However, the best reflection of uniqueness with respect to mega infrastructure construction decision-making is found in the following phenomena. The decision-making subjects must create a decision scheme within a relatively short period of time, and this scheme must guarantee correctness and robustness over a long time. However, due to deep uncertainty within the engineering environment, all possible complex scenarios may emerge and evolve during this extended time period. Thus, the robustness of the decision scheme with respect to the possible scenarios is critical. Without this robustness, the functions of the decision scheme can be damaged or even die during the engineering life cycle, a factor that will directly affect the achievement of the original engineering subjects' intention as well as the value of the engineering itself.

Thus, the effect of the robustness of the decision scheme on scenarios caused by deep uncertainty is a new, unique, and fundamental perspective that is used to measure and evaluate the quality of the decision-making in mega infrastructure construction. This deep uncertainty causes the following:

1. Decision-making activities in mega infrastructure construction, in many respects and links, appear as serious phenomena, such as when data are not accurate, information is incomplete, or the scenario is unclear.
2. The scheme of the decision-making goal and function spectrums in mega infrastructure construction are composed of new features, such as multi-levels, multidimensions, and multi-scales, that appear simultaneously.

3. The adaptability between the function spectrums of the scheme in mega infrastructure construction and the change in the environmental scenario, as reflected by the scenario's robustness, becomes a new objective attribute of decision-making in mega infrastructure construction and becomes the core measurement standard for the quality decision scheme in mega infrastructure construction.
4. Subjects responsible for making decisions must determine the appropriate cognitive factors and then gradually deepen that cognition to resolve deep uncertainties and create a quality decision scheme. From this perspective, a decision scheme in mega infrastructure construction can only be formed through the iterative generation process.
5. Accordingly, new research methods are proposed regarding decision-making in mega infrastructure construction given the feature of deep uncertainty, such as the method of scenario prediction and discovery and the method of measuring and optimizing scenario robustness of the decision scheme.

It is evident that deep uncertainty has a profound, comprehensive, and fundamental impact on the decision-making of mega infrastructure construction and that the features of decision-making, such as multi-scaling and iteration, can be extended or expanded based on these characteristics of deep uncertainty. In this sense, deep uncertainty can be considered the best reflection of the essential features of decision-making activities in mega infrastructure construction. Thus, we call this type of decision-making deep uncertainty decision-making in mega infrastructure construction.

Refining and abstracting the basic attributes of deep uncertainty have important theoretical significance.

First, it reveals the main causes of the complexity of the decision-making activities and decision problems in mega infrastructure construction, which is helpful when designing ideas and a technology roadmap to solve the deep uncertainty decision problems in mega infrastructure construction (Salet et al. 2013; Cao et al. 2011; Perminova et al. 2008).

Second, the concept of deep uncertainty has a close logical relation with the concepts of scenario, multi-scales, adaptability, complexity degradation, adaptability selection, multi-scale management, iterative generation principle, etc. Thus, mega infrastructure construction decision-making is ascribed as a basic concept and principle of mega infrastructure construction management theory, further strengthening the systematicness and logicalization of mega infrastructure construction management theory.

Third, as we demonstrate later, a considerable portion of the method system of mega infrastructure construction management is focused on managing deep uncertainty problems in engineering management, which builds a necessary bridge for specifically solving mega infrastructure construction decision-making problems.

With regard to mega infrastructure construction deep uncertainty decision-making, the logicality of theory thinking is conducive to the further abstracting of the elements of decision-making and the analyzing of the relevance and of the cause and effect. This, then, can form more detailed basic principles and scientific problems regarding mega infrastructure construction decision-making on the level of decision theory.

Although deep uncertainty is the most important attribute of mega infrastructure construction decision-making, it is not the only one. Thus, for the cognition and analysis of mega infrastructure construction decision-making, we still refine and abstract the other concepts and features according to the actual needs of engineering thinking to fully reveal the complexity of mega infrastructure construction decision-making. For example, although the multi-scale of decision goal (function) and the iterative behavior of the scheme formation path cannot be considered the most fundamental attribute of mega infrastructure construction decision-making, they are one side of the complexity of mega infrastructure construction management. Therefore, they play an important role when analyzing and solving the specific problems of mega infrastructure construction decision-making, and they can facilitate the design of the subjects' decision-making behavior criteria and construct the technical path of the decision scheme in practice.

7.2.3 Fundamental Principle of Decision-Making Given Deep Uncertainty in Mega Infrastructure Construction

First, deep uncertainty decision-making in mega infrastructure construction is a type of decision-making. Thus, the fundamentals of general decision-making are also the basic principles of mega infrastructure construction decision-making. For example, the decision-making activities are composed of elements such as decision subjects, decision problems, decision processes, decision goals, and decision schemes (Priemus et al. 2008; Priemus 2010; Chen 2005; Lu 2010). In particular, in science, any decision schemes are the decision subjects' design of the functions of an artificial system where system analysis serves as both the basis of the decision-making process and the assistive technology needed for the decision-making, and accordingly, it is also an important part of the mega infrastructure construction decision-making activities.

With respect to general procedures, the mega infrastructure construction decision-making activities are also decision problem oriented, to determine the overall decision goal, construct alternative decision schemes, and contrast, regroup, optimize, and seek alternative decision schemes by collecting and analyzing the data, information, and materials, using qualitative and quantitative combination methods and computer simulation technology. In this way, a decision scheme is created or the procedure is iterated until a recognizable decision scheme is developed.

Because it is mega infrastructure construction decision-making, it must reflect the basic principles of mega infrastructure construction management activities. For example, according to the principle of complexity degradation and on the bases of engineering goals and function spectrum design, decision subjects properly divide the whole of the decision problem into several independent sub-decision problems, make decisions regarding each of these sub-decision problems, and then achieve their respective decision schemes. Furthermore, based directly on this and under the guidance of the principles of adaptive selection and iterative generation, an entire scheme that is compatible with the sub-decision schemes is generated, or if not, aspects of the sub-decision schemes are modified to form a complete compatible scheme.

Figure 7.10 presents a schematic of this decision-making process.

In addition, at the levels of engineering thinking and operability, all of the mega infrastructure construction decision-making activities are composed of some multi-stage, sub-decision-making activities process that is both independent of and correlated with each other. These sub-activities also manifest as the actual management function in the decision-making practice (see Fig. 7.11).

When considering the fundamentals of the decision-making process, there are principal decision-making behaviors expected of the subjects who engage in the decision-making process. Specifically, the decision-making subjects' values and behavior criteria are intended to solve the decision problems and process and transform the data and information throughout the decision-making process.

Given these two points, how does the mega infrastructure construction decision principle reflect the inherent feature of deep uncertainty and form the technical route and method within the constraints of the established rules?

Quite simply, at the planning and operational level of engineering thinking, the mega infrastructure construction decision principle fully reflects the following:

1. It effectively degrades the complexity of the mega infrastructure construction decision-making that is caused by deep uncertainty, and it proposes the formation route of a decision scheme that reflects the unique quality of mega infrastructure construction decision-making.

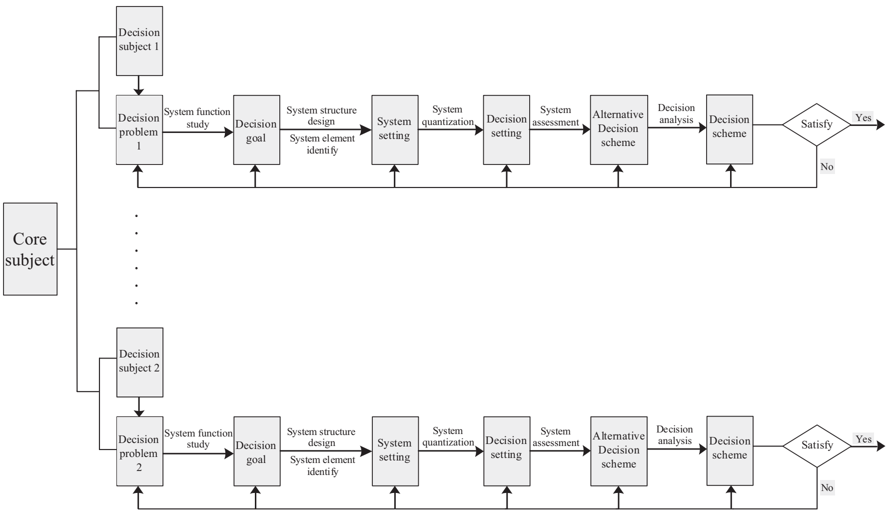

Fig. 7.10 Systematic procedure of mega infrastructure construction decision-making

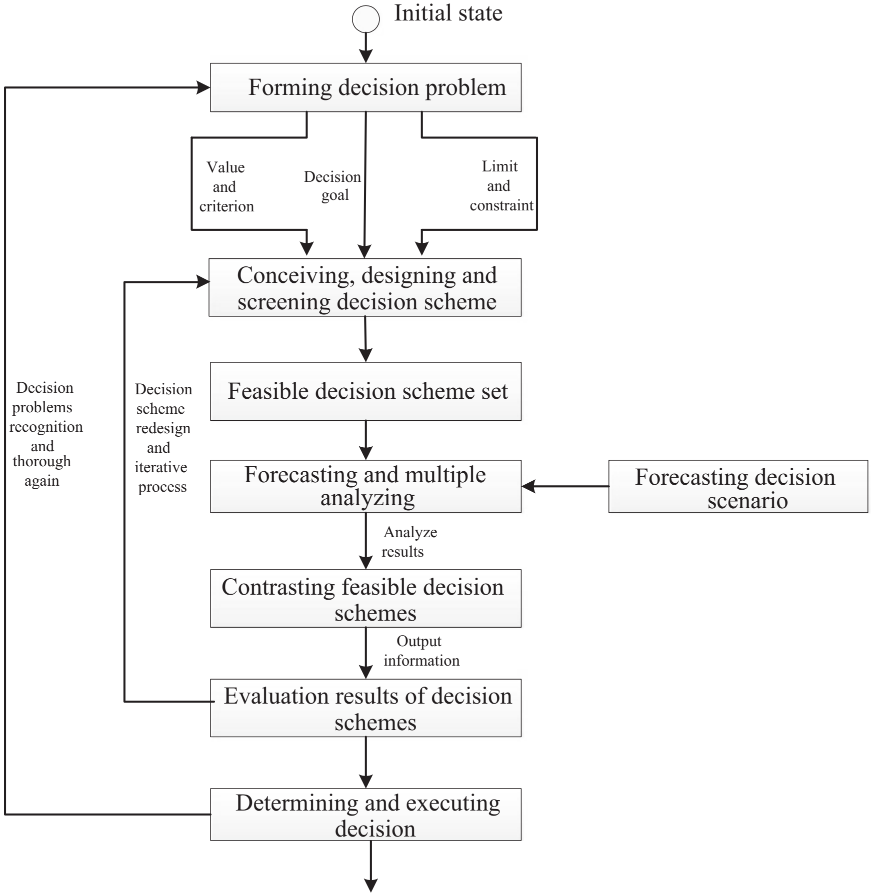

Fig. 7.11 Engineering decision-making process

2. It designs the platform of the organization and the functions of the decision-making process that can be adapted to deep uncertainty.
3. It constructs a method system and decision support system that complements the deep uncertainty.

Without these new cognitions, organization patterns, and key technologies and methods, the unique fundamentals of mega infrastructure construction decision-making have not been realized. Because the mega infrastructure construction decision principle is based on the combined effect of the above points, more complete decision-making behavioral principles, decision procedures, and decision methods can be formed to represent the fundamental, general paradigm of mega infrastructure construction decision-making.

7.2.4 Overview of the Quality of Decision-Making in Mega Infrastructure Construction

With respect to mega infrastructure construction, people often talk about the high and low levels of decision-making in construction, whether there are mistakes made when making decisions (Gu 2011; Xie and Wang 2010). These concerns reflect people's awareness about the quality of the decision-making as it pertains to construction. Thus, the new scientific problems in the field of decision-making in mega infrastructure construction management theory include understanding the quality of mega infrastructure construction decision-making, evaluating and measuring the quality of mega infrastructure construction decision-making, and improving the quality of mega infrastructure construction decision-making.

As is well known, the concept of quality in the field of manufacturing management began with evaluating the quality of manufactured material products. Hence, the people's most direct perception of product quality includes characteristics such as the physical properties of the product materials and the durability and stability of the direct use functions of the product (Business Dictionary; ISO9001:2008). People's initial cognition regarding engineering quality is in this category. Physical properties of the hard system of man-made engineering, such as the strength of the engineering materials and whether the engineering can withstand environmental changes, are used to measure the quality of the engineering (Battikha and Russell 1998; Pries and Quigley 2012).

As the practical connotation of human "manufacture" expands, an increasing number of products whose main characteristics are nonmaterial properties have been manufactured. For example, people's mega infrastructure construction decision-making activities have resulted in products such as decision schemes. This is because, to reflect its existence and effect, the function and role of the decision scheme are no longer focused on the material properties but on nonmaterial properties. In this sense, the decision scheme expresses the prescriptive nature, which is intended to solve a decision problem by designing the function spectrum of a man-made complex system. The components considered when assessing the quality of mega infrastructure construction decisions include whether the decision scheme is reasonable and effective, whether it is stable, whether it satisfies the needs of the people, and whether the degree of satisfaction is sufficient. Accordingly, the following features become evident.

1. The mega infrastructure construction decision-making activities possess the quality attribute. This attribute is embodied as the rationality, effectiveness, and robustness of endowment; thus, it manifests and is enhanced when the mega infrastructure construction decision scheme is used to solve a specific problem.
2. Because the mega infrastructure construction decision-making activity is a type of practice of theory thinking combined with engineering thinking, the decision scheme must embody both the general rules of construction and management and the intentions and value preferences of the decision-making subjects during

the process of construction planning. Thus, regarding the quality evaluation of a decision scheme, we should first respect the objective function and effect of the decision scheme when solving the decision problem. For the decision-making subjects' degree of satisfaction, we consider only the decision-making subjects' values and intentions under the premise of respecting the objective function and effect. Subjects' objective preferences can never exceed the objective laws that are revealed and reflected by the decision scheme. The opposite situation is often the main reason for errors and even major mistakes in mega infrastructure construction decision-making.

3. The primary mega infrastructure construction decision-making activity is the management activity conducted in the front-end phase of construction at the level of engineering insubstantiality (Jergeas 2008; Williams and Samset 2010). Thus, the decision scheme includes the experiences and knowledge of the decision-making subjects when solving a decision problem and fully reflects the decision-making subjects' preset ideals regarding the decision problem. It is well known that the feasibility, rationality, and operability of a decision scheme are required to pass the practice test in the actual mega infrastructure construction activity mega infrastructure construction. Therefore, even if a decision scheme is formed through several iterative approximations, it cannot be assumed that it is perfect. In particular, although mega infrastructure construction decision-making is a type of deep uncertainty decision-making, many deep uncertainties will have the most realistic exposure only in practice, whereas other new and unpredicted deep uncertainties will emerge. Moreover, even if the decision scheme has been formed and the decision-making subject is satisfied with it, there may exist some hidden and potential problems, which means that the decision scheme may need to be improved and changed. In other words, these potentialities indicate that practice is the sole criterion for evaluating and determining the quality of mega infrastructure construction decision-making.
4. For many years, people have confused the quality of engineering with the quality of engineering decision-making, under the impression that if the former is goof, it follows that the latter is good and vice versa. However, this is not the case. For instance, the quality of engineering decision-making refers more to the quality of the design of the man-mad system function spectrum, which is created by decision-making subjects at the level of engineering insubstantiality, whereas the quality of engineering refers more to the physical quality of the man-made system, which is developed by the decision-making subjects at the level of the engineering entity. The former reflects that the idea of the decision-making subjects is either good or bad, whereas the latter reflects that the engineering constructed according to this idea is either good or bad. In fact, there are two possible situations, specifically, one where the decision idea is good but the construction of the project is poor and one where the engineering decision-making is wrong but the engineering construction is strong. Nonetheless, if the engineering is relatively simple, the design of and provision for the function spectrum of engineering decision-making scheme are easy to implement in practice, and the physical implementation path to which the function design in the decision-making

scheme is transformed into an engineering entity is relatively determinate. Thus, the consistency between the quality of engineering decision-making and the quality of engineering is relatively clear. However, with respect to mega infrastructure construction deep uncertainty decision-making, this consistency is not ensured. Therefore, we must not confuse the quality of mega infrastructure construction decision-making with the quality of mega infrastructure construction.

5. The traditional manufacturing industries primarily evaluate the quality of their material products. To assess the quality of decision-making is assessed, for the most part, based on the quality of the decision-making scheme. Whether creating a material product or a nonmaterial one, the decision-making scheme is a manufacturing process that leads to an end result. Therefore, to examine the quality of decision-making, it is necessary to study both the quality of the process that is applied to create the decision-making scheme and the quality of the decision-making itself; i.e., studying the decision-making process can help guarantee better quality decision-making. Accordingly, we must consider and analyze the problem of decision-making quality as part of the whole process of mega infrastructure construction decision-making.

To sum up, it is essential that the basic concept of quality for mega infrastructure construction decision-making be established because doing so can facilitate a deeper understanding of the connotation of the mega infrastructure construction decision-making activity and the attributes of the quality of decision-making. On this basis, it helps us fully explore and discuss how to improve the quality of mega infrastructure construction decision-making.

The quality of the decision-making process includes the structure of the decision-making organization, decision-making procedures, the hierarchical principal-agent relationship between the decision-making subjects, and behavioral norms and deviations.

7.2.5 Scenario Robustness Decision-Making in Mega Infrastructure Construction

In Sect. 5.1.3, we noted that the natural, social, and economic environments of mega infrastructure construction and the large-scale evolution of these environments are the causes of the formation of deep uncertainty features in mega infrastructure construction management activities. Furthermore, for many mega infrastructure construction management activities, this feature has the greatest impact on the decision-making activities related to construction. This is primarily because the decision-making scheme is often developed in a relatively short period of time, even though it must maintain its effectiveness and robustness throughout the life cycle of the construction. However, the original environment system and construction-environment compound system will produce various scenarios that will emerge and evolve and seriously affect the effectiveness and robustness of the decision-making scheme, thereby reducing the quality of the decision-making scheme and perhaps even causing the scheme to fail. This cognition fully reflects our holistic understanding of the various types of complexity of mega infrastructure construction's influence on the mega infrastructure construction decision-making activity. Let us consider and analyze a specific problem. At the time of the construction planning and feasibility studies, which are conducted in the front-end phase of mega infrastructure construction, the decision-making subjects will sufficiently consider the effects of normality and variability of natural, social, and economic environments on the engineering construction. In this case, the decision-making subjects generally consider the environment to be the construction system, and as such, they attempt to embody these effects in the decision-making scheme to implement the coordination between the construction and the environment. Due to the long life cycle of mega infrastructure construction, changes in the environment will expose the deep uncertainties and reveal the types of complex scenarios. Additionally, the design of and provisions for the decision-making scheme must be capable of reflecting the adaptability to impact this scenario, an adaptability that should be sufficiently reflected in the role and effect.

Furthermore, once a mega infrastructure construction is completed, the original environment system and the new mega infrastructure construction form a new man-made system referred to as a mega infrastructure construction-environment compound system (see Sect. 5.1.1). This new complex system may help the decision-making scheme achieve its desired functions, but the emergence and evolution of new system scenarios may also undermine the robustness of its role and effect on the decision-making scheme or even lead to negative roles and effects that were not predicted or expected. The more serious the decision-making is, the more likely it is that deep uncertainty will appear, and the greater the risk is that either damage or mistakes will occur. This, in turn, leads people to assume that the original decision-making scheme was wrong, poorly conceived, or shortsighted. In short, the quality of the decision-making is perceived to be relatively poor and likely to lead to mistakes or cause serious harm.

The aforementioned situations represent two different changes and evolutions of decision-making scenarios. The former considers that the mega infrastructure construction entity has not yet formed and regards the environment as a construction background, which is similar to the exogenous variable of construction. The latter, however, considers that the mega infrastructure construction entity has been formed and that mega infrastructure construction and the original environment have been united to create a new compound system. Both mega infrastructure construction and the original environment system are subsystems of the new compound system, and the environment is similar to the endogenous variable of the engineering system. Regardless of the situation, their influence on the formation of the mega infrastructure construction decision-making scheme, and its quality, is formed by deep uncertainty of the decision-making activity. *Regardless of whether the provisions and stipulations of the mega infrastructure construction decision-making scheme in terms of its role and effectiveness can maintain robustness in the face of change and the evolution of these two types of scenarios, the quality of decision-making scheme* *under deep uncertainty is sufficiently reflected. Thus, this is referred to as the scenario robustness of mega infrastructure construction decision-making. Furthermore*, *we call the former the first type of decision-making scenario robustness problem and the latter the second type of decision-making scenario robustness problem.*

When the decision of navigation capacity regarding the ship lock on China's Three Gorges project introduced in the front of this book was made, the ship lock was insufficient, and congestion resulted because the growth trend of the future Yangtze River's freight volume had been underestimated. This underestimation indicates that the design quality of the function of the ship lock was not high. To solve this problem, it was necessary to build a river in the accessory dam of the Three Gorges and then construct a ship lock on this newly created river. This is the first type of a decision-making scenario robustness problem.

In addition, new problems have appeared in the entire lower reaches of the Yangtze River after storing water from the Three Gorges. Although the downstream water of the Yangtze River is clean, the watercourse has been deeply scoured, the water level has declined by half a meter to one meter, the riverbank has begun to collapse, and the annual water levels of the Dongting and Poyang Lakes have dropped. With respect to the shore collapse of both sides of the upstream Three Gorges, some places that were originally stable are now unstable, forcing the residents to relocate again. This is the second type of decision-making scenario robustness problem.

This example suggests that regardless of whether the first or second type of decision-making scenario robustness problem arises, the change and evolution of the scenario will influence the effectiveness and robustness of the effect on the decision-making scheme and may even induce new, harmful scenarios. Accordingly, *a high-quality mega infrastructure construction decision-making scheme can neither cause a decision-making scheme to lose robustness due to changes and evolutions in scenarios resulting from deep uncertain nor induce new, harmful scenarios after the construction is completed. This constitutes the scientific connotation and significance of scenario robustness in mega infrastructure construction decision-making.*

In a highly open and deeply uncertain environment and under the overall influence of a long-time scale, to consider the quality of a mega infrastructure construction decision-making scheme, we can consider this problem neither at a single point in time or over an extended period nor only statically or dynamically. Rather, we must consider the fit, including the two types of scenario problems, between the role and effect of the decision-making scheme and the changes in the scenarios given the context of the engineering life cycle, the multi-scales, and the evolution and emergence of scenarios. That is, *in the context of the scenario, the role and effect of the decision-making scheme can be both effective and robust with respect to large spaces and time scale changes in scenarios. This cognition is abstracted as a basic concept, namely, decision-making scenario robustness is used to evaluate and measure the quality of deep uncertainty decision-making of mega infrastructure construction.*

Thus, *the robustness of the scenario is the basic property of the quality of mega infrastructure construction decision-making and the objective property of which the robustness or fit of the decision-making scheme related to the change in the environment* *is used to measure the quality of the decision-making scheme*. It must be emphasized that robustness is an overall concept with respect to the stability and fit of the decision-making scheme role within the engineering life cycle. If the environment, including the mega infrastructure construction-environment compound system, is considered a system, and decision-making is considered another (man-made) system, then *scenario robustness is the measure of the coupling degree (fit) between the function spectrum of the scheme system and the environment system of the scenario*.

Environmental scenarios of mega infrastructure construction deep uncertainty decision-making activities are unconventional and may be abnormal and variable. The longer the space-time scale is, the greater the likelihood that an unexpected scenario will appear. This, however, is also more likely to negatively impact the effectiveness of the decision-making scheme. Furthermore, if an unexpected scenario appears, when it appears, and how much damage it causes are all deeply uncertain factors that must be considered. This means that although scenario robustness of mega infrastructure construction decision-making provides a window from which to observe and measure the quality of the decision-making scheme, there are a series of scientific problems that must be explored and solved, such as how to more finely describe the scenario robustness of the decision-making scheme, how to measure and improve the robustness, and how to predict and identify the scenario.

In summary, *if we consider scenario robustness to be the important quality attribute of mega infrastructure construction deep uncertainty decision-making, decision-making activity that is based on scenario robustness to design the decision-making scheme can be referred to as scenario robustness decision-making and can be considered that mega infrastructure construction deep uncertainty decision-making, equated to scenario robustness decision-making.*

In the general decision theory, there is often the concept of an optimal decision scheme. That is, based on certain goals, the decision-making subjects select a scheme that is superior to all alternative feasible schemes. This selected scheme is the optimal decision scheme. However, with respect to deeply uncertain mega infrastructure construction decision-making, it is difficult to accurately and fully propose decision goals and identify an optimal scheme. Rather, a high-quality scheme is one that considers the deeply uncertain factors that are insensitive to the harm which due to the change in a deeply uncertain scenario. This notion is quite different from that of the traditional optimal scheme because it reflects the deep uncertainty of decision-making and the complexity resulting from changes in decision-making scenarios. In this way, it is also considered that *scenario robustness is the optimal mega infrastructure construction deep uncertainty decision-making Scheme.*

7.2.6 Measure and Analysis of Scenario Robustness of Mega Infrastructure Construction Decision-Making

After defining the fundamental concept of mega infrastructure construction deep uncertainty decision-making and scenario robustness decision-making, an important question is how to predict and discover scenarios and how to measure the scenario robustness of the decision-making scheme. Because we have a clear answer and the corresponding method of the two questions, we can evaluate, select, and improve the mega infrastructure construction decision-making schemes.

First, it is important to predict and discover the scenarios, a problem that involves comprehensive new technology. The basic idea of this technology is that any actual mega infrastructure construction decision-making scheme is a man-made system designed by decision-making subjects. Accordingly, this man-made system must have the corresponding system functions and properties. Furthermore, the decision-making scenario can be perceived as representative of the behavior of the entire environment of this man-made system. In this way, the interplay between the system and the environment is analyzed when examining the sensitivity of man-made system functions to changes in the environment, so it can build the technical route of the scenario robustness measure for decision-making schemes.

Specifically, the following methods can be taken together to form the technology that is required to predict and discover decision-making scenarios.

1. According to the properties of the decision problem, decision-making subjects use their own professional knowledge and experience to conduct projections and make qualitative predictions.
2. The decision-making subjects use relevant data and information to identify correlations and establish the structure of the scenario analysis necessary to make some quantitative predictions.
3. The most important environment trait should be the core statement of the respective scenario, and as such, it should be termed the core scenario of the scenario. Accordingly, the core scenario must be conceptualized and structured using a language that a computer will understand. Then, using computer simulation technology and the scenario modeling method, a scenario space can be generated. Portions of these contexts can be seen in Sect. 9.2 (Scenario farming) of this book.

Based on the above and a combination of other steps, such as checking and verification, certain results of scenario discovery and prediction can be proved.

In theory, the predicted future scenario space is exceptionally large. That is, this space may contain a considerable number of scenario points. Thus, regarding the scenario robustness of the decision-making scheme, many of the scenario points may be the normal points of the environment, and as such, they represent the common and stable traits of the further decision-making environment. Although these traits may fluctuate, they generally do not cause the effectiveness of the decision-making scheme to fail. Accordingly, the significance and role of these scenario points are considered to be trivial with respect to the decision-making scheme. However, there is another type of scenario point in the scenario space whose traits and fluctuations may significantly damage the normal effect of the decision-making scheme. Therefore, regardless of the likelihood of the scenario points, every effort should be made to prevent them. When making decisions in mega infrastructure construction, the decision-making subjects often propose the once-in-a century quality and safety standards with the aim being to prevent the occurrence of these harmful types of scenarios, which, although they are rare (once in a century), cause great harm to the robustness of the function as designed by the engineering decision-making scheme.

Although this serious type of scenarios is less likely to occur, its occurrence seriously damages the robustness of the decision-making scheme. Therefore, this type of scenario is referred to as an extreme scenario. The proposal of this concept has important practical significance when establishing a method that can evaluate and select the mega infrastructure construction scenario robustness decision-making scheme in that this type of extreme scenario becomes the threshold from which to judge the mega infrastructure construction scenario robustness decision-making scheme. If the decision-making scheme can show robustness when facing this type of extreme scenario, then the robustness of the decision-making scheme for other scenario points in the scenario space is guaranteed.

However, since the scenario space of engineering decision-making is too large, the extent of the extremeness in the extreme scenario also depends on the values and preferences of the decision-making subjects as well as on certain objective standards. For example, we only consider the once in 10 years extreme scenario or the once in a century extreme scenario when selecting a decision-making scheme. Therefore, decision-making subjects must consider not only the possibility of the extreme scenario and its level of potential harm but also the implementation cost and the degree of difficulty with implementation. That is, the final confirmation of the extreme scenario must comprehensively consider various factors, including the degree of damage to engineering caused by the scenario, the possibility of the extreme scenario occurring, the implementation cost, and the feasibility of executing the decision-making scheme.

After defining the technical route, a method for measuring the extreme scenario robustness of the decision-making scheme must be designed. Thus, the academic idea with respect to this method is followed. First, a decision-making scheme that has the requisite satisfactory robustness must be identified by the decision-making subjects. This scheme is then used as a reference scheme. A performance index that is closely related to the robustness attribute is designed based on the performance index given by the reference scheme. The decision-making scheme and performance index are then evaluated, and the gap of the index values between the schemes is transformed into the lack of robustness of the evaluated scheme. The key is that the method of transformation is related to both the objective attribute of the scheme and the decision preference of the evaluation subject. Thus, the values of the different evaluation subjects' and their psychological preferences regarding decisions will result in different trade-off attitudes toward the same decision-making scheme. This is best evidenced in the various constructed transformation methods.

For example, for a future extreme scenario, decision scheme *a* has a corresponding performance, such as value and effect, as denoted by $\text{Performance}_{\text{v}}(a, S_{\text{e}})$. If decision scheme *a* is adopted and an extreme scenario appears, then the decision-making subject inevitably suffers risk or loss. The pessimism value that is caused due to this is (Wald 1950):

$$\text{Pessimism}_{\text{v}}\left(a,S_{\text{e}}\right)=\frac{1}{\text{Performance}_{\text{v}}\left(a,S_{\text{e}}\right)}$$

where the decision scheme a belongs to the scheme set $A\,(a \in A)$ and the extreme scenario s_e belongs to the scenario space $S(s_e \in S)$, which is found by various technologies such as scenario farming.

The final scheme is then determined by the criterion $\min_{a \in A}\left\{\text{Pessimism}_v\left(a, S_e\right)\right\}$. Obviously, the justification for selecting a decision scheme based on the minimum pessimism value is to find the most favorable scheme relative to other schemes under the most unfavorable conditions as based on the extreme scenario. To select the scheme with the minimum pessimism value means that the decision-making subject can rely on the robustness of the scenario.

For another example, if the above method, which begins with the worst case extreme scenario, is too conservative, the following method inspired in the thought of Lempert's method can be considered, which evaluates the decision scheme through the regret value (Lempert et al. 2006). The premise behind this method is that the decision subject selects the scheme. When this scheme encounters a future extreme scenario and is compared with a satisfactory scheme relative to the extreme scenario, it would cause some loss due to the lack of robustness of the scheme. Therefore, the decision subject will experience remorse and regret. If we cannot completely avoid the regret caused by the deep uncertainty, we can at least select a decision scheme according to the principle such that the inevitable regret is not too serious.

Accordingly, the definition of the regret value for the decision scheme is as follows. The difference between the performance of decision scheme a under extreme scenario s_e and the performance of a satisfied scheme under the same extreme scenario is the regret value of scheme a (Savage 1951). That is,

$$\text{Regret}_v\left(a, S_e\right) = \max_{a'}\left[\text{performance}_v\left(a', S_e\right)\right] - \text{performance}_v\left(a, S_e\right)$$

where, in all schemes, decision scheme a' is the best performance scheme under future extreme scenario $(a' \in A)$ and extreme scenario s_e belongs to the scenario space $S, (s_e \in S)$.

The minimum regret value $\min_{a \in A}\left\{\text{Regret}_v\left(a, S_e\right)\right\}$ is then selected, and the scheme that corresponds to this minimum regret value is the scheme selected by the decision-making subject. Specifically, this method first measures the regret values of all decision schemes under the extreme scenario and then determines the maximal regret value of each scheme before selecting the minimum regret value from all maximum regret values. The decision scheme corresponding to this minimum regret value is the optimal scheme given the robustness of the extreme the scenario.

Of course, if the decision-making subject thinks that only considering the extreme scenario when selecting a scheme is too extreme, the extreme scenario can also be comprehensively considered with a non-extreme scenario. This idea could be adopted when the possibility of the extreme scenario occurring is extremely small or the scheme cost under the extreme scenario is too great.

Another example, the decision-making subject considers both the performance of decision scheme a under extreme scenario s_e, which is denoted by $\text{Performance}_v(a, s_e)$, and the performance under the non-extreme (general) scenario s_g, denoted by $\text{Performance}_v(a, s_g)$. The subject then eclectically considers measuring the scenario robustness of decision scheme a under the two scenarios. At this point, the eclectic (weighted average) performance of decision scheme a under extreme scenario s_e and general scenario s_g is defined (Hurwicz 1951):

$$\text{Eclectic}_v\left(a, s_e, s_g\right) = \beta \ \text{Performance}_v\left(a, s_e\right) + \left(1-\beta\right)\text{Performance}_v\left(a, s_g\right)$$

where $\beta \in (0, 1)$is the eclectic coefficient.

The decision scheme corresponding to $\max_{a \in A}\left\{\text{Eclectic}_v\left(a, S_e, S_g\right)\right\}$ is selected as the optional scheme. Accordingly, the selection principle based on the eclectic performance reflects the decision-making subject's safe and positive decision preference.

As previously mentioned, although the scenario robustness is the objective attribute of scheme quality of mega infrastructure construction decision-making, it is difficult to measure the scenario robustness of the scheme and reflect the decision-making subject's decision preference and subjective value because, generally speaking, when measuring the scenario robustness of a decision scheme, the above objective attribute will be changed into a subjective value of the decision-making subject. Thus, it is difficult to say that there is only one method or only one unique measured value when measuring the scenario robustness of a mega infrastructure construction decision-making scheme. In contrast, using different measuring methods will yield a number of scenario robustness decision-making schemes in various contexts. This phenomenon reflects the profound effect of deep uncertainty in mega infrastructure construction decision-making on decision problems and decision-making subject's behavior.

In general, mega infrastructure construction deep uncertainty decision-making, especially the quantitative analysis method of scenario robustness decision-making, is a scientific problem that has recently emerged and now dominates the academic frontier.

7.3 The Finance in Mega Infrastructure Construction

At the end of the Second World War, many countries engaged in large-scale infrastructure construction by allocating funds, government loans, and loans to financial institutions. However, in the 1970s, developing countries borrowed heavily because the international debt crisis had intensified. With the increase of project investments, governments found it difficult to advance more money to meet the increasing demands of major construction projects. In the beginning of the twenty-first century, an increasing number of mega projects focusing on a long-term development strategy of domestic and international competitiveness began to emerge, and thus, a shortage in the construction fund for mega projects is becoming more common and more serious.

The relationship between mega infrastructure construction and capital resources has been discussed, and the characteristics of capital resources, funding sources, and difficulties in raising money during the process of construction have been analyzed in this section. Furthermore, the connotation of investment in mega infrastructure construction and financing has been examined, and the basic characteristics of mega infrastructure construction investment and financing have been analyzed. As a result of the analysis, its economic attributes and their limitations were identified. To solve these limitations, this section proposed a scientific concept of finance in mega infrastructure construction and conducted a thorough system analysis. Finally, this section expounds the basic circumstance on behalf of the Asian Infrastructure Investment Bank (AIIB) and proposes a number of scientific questions in the field of finance in mega infrastructure construction.

7.3.1 A Construction Fund in Mega Infrastructure Construction

Capital is an indispensable resource for construction projects, especially for mega infrastructure construction projects. Given the new historical situation, the acceleration of Chinese urbanization and the appearance of the One Belt, One Road policy, a new upsurge in infrastructure construction, are occurring.

For general projects, there are many resources and channels for building funds that can be divided into different types. For example, according to the accounting relationship, the source of funds can be divided into equity capital and debt capital; according to nationality, the source of funds can be divided into domestic capital and foreign capital; and according to the channels of funding, the source of funds can be divided into personal funds, loans for capital, and money for leasing. According to the channel and the path of the funding source, project fund financing channels can be divided into funding, policy bank loans, commercial bank loans, securities, trust companies, industry funds, and other social capital. Furthermore, several aspects of the source of funds accounting relationship can be divided into equity capital and debt capital. The source of funds regarding nationality can be divided into domestic capital and foreign capital. The source of funds can also be divided into personal funds, loans for capital, and loans for leasing. According to the channel and the path to the source of funds, project fund financing channels can be divided into policy bank loans, commercial bank loans, securities, trust companies, and industry funds as well as social capital and other funding sources (Yan 2014). These different types of fund resources can solve most general projects' funding problems; however, for mega infrastructure construction, these funding resources are far from adequate.

From the perspective of mega infrastructure construction, the capital resources of mega projects reveal substantially different characteristics from general projects.

The first difference is the significant difference in the funding required for general construction compared to that required for mega infrastructure construction. With respect to mega infrastructure construction, neither the fiscal appropriation nor the bank loan can provide the requisite funds needed for the project. The traditional infrastructures in China were created during a special time to meet the national shortage of infrastructures. Due to the country's poor productivity, development level and technology level, the infrastructures were built to meet only the basic needs of the national people. The stages for project funding included fiscal appropriation, loans from banks, loans from international financial institutions, and project financing of franchises. Accordingly, it includes not only the advancement from domestic economic development to overseas development but also the demand from the fund's lack of infrastructure during the process of finding different funding resources.

Since the beginning of the twenty-first century, global economic integration has rapidly increased, and technology has continued to advance at unprecedented rates. Modern high-speed railways, subways, and cross-sea bridges across the rivers in the artery of the national development of the twenty-first century are among the major mega infrastructure construction projects planned not only to meet the basic travel demands of domestic residents but also to focus more on the future of national strategies and national interests. It is thus urgent to fund this mega infrastructure construction project. The billions of dollars invested in mega infrastructure construction indicate that it is far more than any business, bank, or consortium can bear. It is even a huge burden of the finances of the government. In recent years, China has built several mega projects, some of which have cost less than 100 billion RMBs and others that have cost more than 100 billion RMBs, the latter of which heralds an important demand in funds for mega infrastructure construction in the future (You and Guo 2014) (Table 7.4).

Table 7.4 Mega projects in mega infrastructure constructions in China

Project name	Amount of planned investment (unit: billions of RMB)	Project name	Amount of planned investment (unit: billions of RMB)
China High Speedway	900	Haerbin-Dalian High-Speed Railway	92.3
The Silk Road plan	280	Hong Kong-Zhuhai-Macao Bridge	100
Beijing-Shanghai High-Speed Railway	220	Natural Gas Transmission from Sichuan to East China project	62.7
Shanghai-Chengdu High-speed Railway	170	South-to-North Water Diversion project	500
Lingang new city	150	Yangshan Deep Water Port	50
Wuhan-Guangzhou High-Speed Railway	116.8	Nanjing Metro Line 2	10.9

Source: China media and report

Second, mega infrastructure construction has a single funding source and a shortage of funds. Not only can the traditional financing mode not satisfy the large demand in mega infrastructure construction, but even the model whereby the government of the country provides all of the necessary capital for the construction is unsustainable. Furthermore, private participation and franchising as the main characteristics of the project financing model are powerless because of huge investment funds. The conflict between the large demand and the shortage of social and government financing has become one of the key issues hindering the development of mega infrastructure construction in the long run (Amila et al. 2014). With the development of the economy, the progress of society, the unprecedented increase of movement in population and in logistics, so the demand for large infrastructure projects has grown; as a result the standards for such projects are becoming higher. However, for quite a long time, the main investor in mega projects in China has been the government, and the funds have been allocated from the fiscal budget. However, since the 1990s, certain project financing modes such as BOT have begun to gradually enter the country and have been successfully applied in the general field of infrastructure construction projects. That said, in the field of mega infrastructure construction, a successful model has yet to be developed (Fei 2004).

In the current investment and financing system dominated by the state, the large financing gap has become a bottleneck that restricts the development of infrastructure construction on a global scale. In Asia, for example, according to the calculations of the Asian development bank, in the next 8 to 10 years, the Asian infrastructure fund demand will reach 730 billion dollars a year. Similarly, the World Bank estimates the demand to be approximately $800 billion annually. Now, according to the latest data from recent measurements, the Asian Development Bank and the World Bank's two largest financial institutions in the region report total infrastructure investments for each year to be approximately $30 billion, and even though the World Bank group, ODA, in the developed countries is considered, it is still difficult to close the funding gap (Kayser 2013). Thus, infrastructure construction is facing a huge funding gap in Asia. Moreover, on a global scale, the World Bank statistics indicate that the capital formation rate is low and that middle income countries' share of the GDP is approximately 25%; however, which including funds for infrastructure investment, it is only 20%, or approximately $400 billion relative to the trillions of dollars being demanded. Thus, it is evident that there exists a huge gap with respect to infrastructure construction financing (Yao et al. 2006).

Finally, financing difficulty in mega infrastructure construction is a prominent problem in developing countries that are delegated by China. Although, in recent years, China's government has promoted the PPP mode in project construction as a way to guide social capital toward the mega infrastructure construction, this is limited to business projects and smaller construction projects. Because the investment cycle is long, the investment is substantial, and the risks and rewards are unclear, the investment of social capital in mega infrastructure construction remains low (Byoun and Xu 2014; Lu et al. 2015b).

In addition, financial institution loans and syndicate loans, which are widely used in international projects, face numerous challenges in China. For a long time, the main loaner in China was the state-owned enterprise, and the bank's business was limited. Due to the lack of understanding regarding project financing and the lack of successful experiences, the bank often required joint guarantees from the parent company when processing project loans to expand the scope of the project loan recourse and circumvent the risks. This increased the difficulties in obtaining financing and increased the cost of financing, which, when combined with the international syndicated loan applications of China's legal system, restricted the development of project financing in China (Fan et al. 2007; Liu et al. 2014). Finally, because related laws and regulations tend to lag, the absence of the role of government is an institutional factor that contributes to China's project financing difficulties.

7.3.2 Investment and Financing of Mega Infrastructure Construction

7.3.2.1 Investment and Financing in Mega Infrastructure Construction: Overview

Investment and financing in mega infrastructure construction is a compound scientific term consisting of two key elements: mega infrastructure construction and investment and financing. The former is the definition of the object of this scientific concept, whereas the latter is the definition of the behavior of this scientific concept. Based on the understanding of mega infrastructure construction and investment and financing, investment and financing in mega infrastructure construction can be defined intuitively as the investment and financing activities that are conducted to realize and understand the activities involved in mega infrastructure construction. That is, investment and financing in mega infrastructure construction includes connotations in two dimensions: investment and financing.

The investment in mega infrastructure construction is the funding and output estimation process with respect to mega infrastructure construction (Winsen 2010; Rajiv et al. 2015). The characteristics of an investment in mega infrastructure construction are manifested in four ways. First, an enormous investment amount is the primary characteristic of mega infrastructure construction; second, as the investment fund for mega infrastructure construction is input periodically as the construction progresses, the long-term project construction cycle determines the long-term mega infrastructure construction investment; third, the input of any fund is directly transferred into a specific category of the mega infrastructure construction project to prevent it from being used as a fund for another investment, i.e., ensuring the nonliquidity of the investment; and fourth, as the investment amount for mega infrastructure construction is tremendous and profits cannot be acquired through users' payments to utilize the products and services during the operation of the mega infrastructure construction, the recovery of the mega infrastructure construction investment tends to extend over decades.

The financing of mega infrastructure construction is, essentially, the fund-raising process for the mega infrastructure construction project, a process that involves the economic evaluation of the mega infrastructure construction, the selection of financing schemes, the project investment funding and cost control, and the selection of the financing model. First, there is limited recourse, which means that banks can only recover the loan from the debtor through the project's cash flow and assets when the debtor is unable to repay the bank loans, thus differentiating it from traditional financing, which is characterized by full recourse. Second, with respect to the investors of the project, if the loan arrangement of the project is fully reflected in the balance sheet of the borrower's company, the asset-liability ratio of the borrower's company will likely be out of balance and exceed the acceptable range of the bank. Thus, the off-balance sheet financing arrangement is often adopted. Third, because the mega project financing activities span a wide range, the financing process is complex, and the risk factors are many, site negotiations that involve many factors are required, and numerous written paper certificates and hundreds of legal documents are needed, all of which contribute to the high cost of mega project financing. Furthermore, the large scale of the mega infrastructure construction investment determines that investors cannot operate with their own financial power as they are not willing to undertake such huge risks. Therefore, the other participators and borrowers with direct or indirect interest relationships with the investors and the project all share in the risks.

7.3.2.2 Development of Mega Infrastructure Construction Investment and Financing Models

China's economic system has undergone a transition from a planned economy to a market economy. At the same time, the investment and financing mode of mega infrastructure construction in China has produced different patterns under the background of a social and economic system, that is, from a planned economy under the financial allocation of a single investment and financing mode to a model of government lending and social capital participation, which has eventually evolved into today's diversified investment and financing mode of government guidance and market operation.

1. The investment and financing model based on financial allocation under a planned economy.

For many years, the government of China, per the planned economic policy, provided the infrastructure for the country. This meant that the investment, construction, management, and operation of infrastructure projects were completed by China's government and, as such, that the fund resource was the country's fiscal budget. Investments in infrastructure construction not only depend on state and local government finances, but they also depend on the government investment policies and plans, which include government budgetary expenditures and policy tolls; i.e., government budgetary expenditures include three parts, the central fiscal budget earmarks, "two dollars," and the local government earmarks, and the local government funding policy fee refers to tolls.

2. The government-led investment and financing model – characterized by loaning instead of allocating.

After the 1980s, i.e., after the development of the reform and the opening of China, the development of China's national economy increased relatively quickly. At the same time, the policy on tax cuts was implemented for enterprises, causing the proportion of fiscal revenue to national income growth to slow and residents' incomes to improve greatly. As the demands for the funding of infrastructure construction could no longer be satisfied solely by financial allocations, the bank loan became an important source of funding for infrastructure construction. The financing model of loaning instead of allocating was implemented in the field of infrastructure construction in China. Overall, although the government still occupied a leading position, the difficulties in construction funding could be approached through loans from financial institutions such as banks. Furthermore, as the toll collection policy was adopted after the completion of the infrastructure construction projects, the infrastructure projects were equipped with the operational feature, thus laying the foundation for the participation of social capital in the 1990s. Since then, countries have implemented indirect financing whereby banks occupy a critical position in the field of infrastructure, and the infrastructure funding is from paid to unpaid loans.

3. The government-led and social capital involved investment and financing model.

From the mid- to the late 1990s, the new investment and financing system was gradually confirmed. Of the main characteristics of the system, the first involves dividing the investment projects into three types: public benefit type, basic type, and competitive type. The public benefit type was invested in and constructed by the government, whereas the basic type was invested in primarily by the government, but it also received investments from companies and from foreign investors. Conversely, the competitive type was invested in and constructed by the companies. Second, the loaning instead of allocating method was terminated, and the government investment responsibility was gradually transferred from the central government to the local governments. The most distinct feature of the investment and financing reform during this period was that they created conditions for the entry of social funds for infrastructure construction and facilitated the diversification of infrastructure investment subjects. In addition, with the increase in the quantity of domestic mega infrastructure construction projects, government investment companies were established and became the main source of investment and financing. During this period, as the market-oriented operations of the large projects in China began to build, the investors in mega infrastructure construction projects began to present the preliminary trends of diversification. In addition to the government and the state-owned investment company, the institutional investor and foreign investor gradually began to participate in financing mega infrastructure construction. With respect to indirect financing, in addition to commercial bank loans, policy loans from national development banks and foreign financial institutions as well as government loans become an important source of funds for mega infrastructure construction.

4. Diversified investment and financing model led by the government and operated by social capital.

Beginning in the twenty-first century, the infrastructure construction in China gradually formed a new pattern of government-led social involvement and market-operated industrial development. The development resulted in three diversifications, namely, diversified subjects, diversified channels, and diversified means, which led to the emergence of many investment and financing models including financial attribution, public collection, enterprise financing, Sino-foreign joint venture, and the BOT and PPP models. The allocation function of financial budgets for social resources was gradually transferred to the market, the infrastructure investment became an important part of the total investment in society, and the diversification of investment subjects became the inevitable tendency of reform. At the same time, China's economy entered a rapid growth period, and a surging demand for infrastructure in the real economy increased. Compared to the huge infrastructure investment demand, the single fiscal investment led to an enormous capital gap. Thus, the most important endeavor was to attract the participation of social capital and spread the financing channels. Accordingly, the infrastructure investment and financing mode of China officially opened a new round of specifications and the road to reform. As an important part of the total social investment, actively attracting social capital and expanding investment and financing channels is an inevitable trend for infrastructure construction investment.

7.3.2.3 Interpretation of the Investment and Financing Model in Mega Infrastructure Construction from the Perspective of Economics

According to the principle of public economics, the project can be divided into three types: private products, quasi-public products, and public products. The characteristics that distinguish them are competitiveness and exclusivity. Competitiveness is a characteristic that a product can provide to a consumer rather than a service that can be provided to multiple customers simultaneously. Exclusivity means that the product is available only to those who can pay for it. Competitiveness and exclusivity make possible the production of private goods and the trading of those goods in the market, and the characteristics of those public goods are competitive and nonexclusive. In other words, public products can be collective but free, such as radio access, city square admittance, and free parking. Quasi-public products are those products that possess characteristics of both private and public products, such as toll roads. Accordingly, most mega infrastructure constructions belong to quasi-public products. More specifically, mega infrastructure constructions exhibit the features of private goods. For example, the toll highway adopts the principle of "whoever pays the toll can enjoy the services," and the non-competitiveness of its passage is limited. Conversely, mega infrastructure constructions exhibit features that resemble those of public products, i.e., with respect to the services offered by highways, subways, bridges, and tunnels, the capacity of these services is non-competitive within a certain range (Altshuler and Luberoff 2003; Perminova et al. 2008). Both factors determine the quality of mega infrastructure constructions as quasi-public products.

Second, the economic effect of mega infrastructure construction investment is an external effect that refers to the nonmarket influence of the behaviors of market participants on other market participants. In terms of mega infrastructure construction, although the value can be measured with such direct economic indicators as the investment payoff period and the amount of profits acquired, the more important value of mega infrastructure construction is reflected in the social and economic externalities, i.e., the indirect benefits.

Except for the quasi-public product and external effect of investment, the investment in mega infrastructure construction has a macroeconomic effect. The Keynesian macroeconomic theory indicates that the projects have a stimulating effect on a macroeconomy that is reflected by a demand effect and a supply effect. Under the influence of the demand effect, the project investment promotes improvement in the economic growth and economic efficiency of the country, especially in developing countries. The supply effect of the infrastructure means that the infrastructure can expand the productivity and then influence the total social supply while simultaneously increasing the capital stock (Yunbi and Keith 2010). The pump-priming effect of infrastructure investment is based on modern investment theory, which states that, on the one hand, the productivity of private capital can be enhanced indirectly by improving the level technology level and, on the other hand, that the benefits from the investment in infrastructure can attract private capital. In recent years, research has concluded that, from the perspective of the scientific proposition, infrastructure investment promotes economic growth. As such, the investment's internal mechanism is embodied in five aspects. First, an investment in infrastructure can increase output, stimulate private investment, and increase employment; second, the production factors of infrastructure increase other inputs; third, an investment in infrastructure improves the private investment in production capacity; fourth, an investment in infrastructure reduces the enterprise inventory; and fifth, an investment in infrastructure produces internal revenue. All in all, an infrastructure investment, especially an investment in mega infrastructure construction, has a macroeconomic effect on two levels by creating supply and demand, and it drives economic growth.

Accordingly, an analysis of the economic effect of investment and financing in mega infrastructure construction involves three perspectives, which of the investment feature of quasi-public goods, the investment itself, and the economic externality with respect to the macroeconomic effects of mega infrastructure construction. These three perspectives of investment and financing in major projects define the economic attributes and highlight the economic connotation of investment and financing in mega infrastructure construction. The economic perspective of investment and financing in mega infrastructure construction has established a good theoretical foundation. However, such an analysis is greatly limited, as reflected in the lack of deep cognition regarding the key terms, namely, investment and financing and investment and financing in mega infrastructure construction. The investment and financing in mega infrastructure construction is a compound scientific term, and as such, the economic understanding of this scientific concept involves an understanding of mega infrastructure construction and investment and financing. However, the existing analysis of investment and financing in mega infrastructure construction focuses more on mega infrastructure construction as an object but ignores the definition of the economic scope of investment and financing.

The current literature related to project investment and financing provides a preliminary understanding of the concept of economics whereby project financing is presented as international finance in many books. This projection, however, is unreasonable as international finance is a system involved in the balance of payments, international exchange, international settlement, and international credit. That is, it is a discipline of international investment and international monetary exchange. The only similarity between project investment financing and international finance is that of international investment. However, international investment can realize the economic value added by multinational monetary capital investment subjects or by cross-border capital flow and operation, which is different from project investment and financing. Although there is participation of foreign capital in project investment and financing, especially in the investment and financing of mega infrastructure construction, it is unreasonable to equate project investment and financing with international finance. In addition, studies have portrayed project investment and financing as project economics, project investment, and project finance and economics (Bonetti et al. 2010; Taylor and VanMarcke 2005; Wang and Yang 2000). However, these deductions are based more on the operations at the technical level, rather than on a theoretical or scientific definition of the problem. Accordingly, to provide a possible solution to this problem, a scientific problem was proposed that could fully include the connotations of investment and financing in mega infrastructure construction and an in-depth analysis of the scientific problem was conducted.

7.3.3 Mega Infrastructure Construction Finance

7.3.3.1 Proposal of the Problem

Mega infrastructure construction correlates to the development of the national economy, people's livelihood, and national long-term planning. Thus, it is a complex system that begins with the argument and progresses to financing, construction, and operation. Of these, the raising, arranging, scheduling, and use and risk management of mega project construction funds constitute the mega project financing system (Luo 2006a, b; Rausch 2011; Tolone et al. 2004). Given such a complex, systematic project that involves national strategy and objectives, the source of the funding as well as the integrated financing system arrangement and risk management design must be defined. The public project financing model represented by the agent-construction system, build-operate-transfer, build-transfer, and public-private partnership and the classic project financing model represented by product payment, leveraged lease, and ABS asset securitization could solve the source of funds for general projects. However, for mega infrastructure constructions, the selection of the financing model and the source of funds are only the basic factors of the financing system. Thus, from the perspectives of system arrangement and overall planning, the construction of the financing system for mega infrastructure construction is a more basic and important scientific problem compared to the study of mega project financing. From the perspective of finance, the mega infrastructure construction financing system could be called mega infrastructure construction finance.

The proposal of mega infrastructure construction finance is not a pure creation of an academic term, but rather, it originates from its profound practical basis and developmental background of the times. Since the start of the twenty-first century, mega infrastructure constructions in China, ranging from millions of RMB to tens of millions of RMB, were constructed rapidly. Furthermore, a series of long-distance, high-speed rails, subways crossing the river, and bridges crossing the sea were included in the national plan, which formed the profound project's practical basis. In 2013, the development planning of One Belt, One Road policy was proposed, and the Asian Infrastructure Investment Bank (AIIB) was built and established in 2015, thus forming the development background of the era. When the AIIB was established in 2015, the infrastructure construction entered into a new period, meaning that the mega infrastructure construction project not only had a specialized international funding source but also had a specialized restricted system with a professional fund management department (Yuge 2014).

7.3.3.2 Academic Definition of Mega Infrastructure Construction Finance

Mega infrastructure construction finance is the joint result of the constantly emerging mega infrastructure construction and the major adjustments to the global public product financing pattern. As such, it has a specific time background, special connotations, and distinct boundaries, features and functions. Compared to project financing, the range of mega project financing is more extensive, the time background is more apparent, the practical value is better, and the significance of the science is stronger, all of which lead to new problems. However, because the traditional project financing theory cannot completely resolve these problems, it is important and urgent to create a mega infrastructure construction finance system based on theory and practicality (Ravanshadnia et al. 2012; Sanderson 2012; Stefanie and Roald 2010). One of the most basic problems is the systemic understanding and scientific definition of mega infrastructure construction finance. In view of the complexity of the system, the major project financial boundaries include the openness of mega infrastructure construction as well as the funding arrangement, capital operation, financial risk management, and numerous problems that play decisive roles throughout the project period. For the understanding of mega infrastructure construction finance as a scientific concept, several problems must be solved.

First, the basic features of mega infrastructure construction finance are analyzed. Mega infrastructure construction finance is a new concept with new wording, and it has its own specific background. As a type of financing arrangement theory, it not only has some basic features of general project financing, but it also has some new connotations and features. Second, the understanding of the basic functions of mega infrastructure construction finance is the core problem related to the academic concept of mega project finance and the integrated reflection of its practical value and theoretical significance. Third, the organization and implementation of mega infrastructure construction finance include the participants of mega infrastructure construction finance, the functions of the participants, and the mutual relationships among the various participants. Fourth, with respect to the administration problem of mega infrastructure construction finance system, because mega infrastructure construction often requires a long cycle and faces great difficulties, the financing risks are high, especially when considering that transnational mega infrastructure construction investment face numerous complex factors. Therefore, solving the administration problems regarding investments in transregional and transnational mega infrastructure construction is an issue that requires attention.

Accordingly, *mega infrastructure construction finance refers to the financial activities generated to satisfy the fund demands of mega infrastructure construction. Thus, such activities with specific objectives and specific functions can make the raising, scheduling, arranging, and managing of the funds of mega infrastructure construction more systematic, institutionalized, and internationalized and can build an administration system for mega infrastructure construction finance in an open environment.*

According to the connotation of mega infrastructure construction, there are several obvious characteristics.

First, mega infrastructure construction orientation is the fundamental characteristic of mega infrastructure construction finance, and a series of investment and financing activities conducted according to the planning and scheduling of mega infrastructure construction completely encompass and surround the mega infrastructure construction itself. Because mega infrastructure construction finance is project oriented, the large-scale and collective financing activities of the project initiator or investor are possible. In the field of corporate finance, the financial assets and corporate credibility are often regarded as the corporate financing guarantee. However, with respect to mega infrastructure construction, even a company with abundant financial strength does not always possess the required funds to implement the project. In the frame of mega project financing, which is oriented toward the project, taking several factors, such as government support, social benefits, and economic impact into account, not only can the project obtain more capital, but it can also be given an extended loan period.

Second, although mega infrastructure construction finance does not consider maximizing profits as its objective, such finance can cause a powerful overflow in social economic benefits. Mega infrastructure construction has huge investments, long cycles, and a frequently flowing capital chain where the value appreciation is achieved through the transfer of capital flow between departments. Thus, the overflow of economic benefit is incurred. For example, assets of mega infrastructure constructions are unique from government funding, and thus, private consortiums, which can be securitized, can trade in the capital market through investment banks. These private consortiums with securitized bonds can then list and trade these securitized bonds to raise large amounts of money to further promote the development of the social economy.

In the financial field, whether the traditional pattern of the financial organization represented by Internet finance and corporate finance or the information era financial organization mode represented by international finance and supply chain finance is the common feature that is realized as the value of appreciation and capital profit maximization, mega infrastructure construction is characterized by the quality of the public product, and its most fundamental objective is to satisfy the needs of the social public rather than to achieve maximum profits. However, the nonprofit maximization of mega infrastructure construction finance does not mean that its fund use is completely of public benefit or that it totally ignores cost and interest but rather that the flowing fund in the mega infrastructure construction finance system abides by the general law of the market, realizes the value transition and appreciation in the flow, and makes up the market profits it should receive through the toll for public products.

Finally, the system of mega infrastructure construction finance is a multi-risk own characterized by multi-credit agents. The credit structure agents under the financial system of mega infrastructure construction are the suppliers of the mega infrastructure construction fund, including the government, banks, private consortiums, foreign banks, trust funds, and insurance companies. Thus, it is a credit structure with multiple subjects and multiple layers. The last feature of mega infrastructure construction finance is the diversification of risk uncertainty, which includes credit risk, financial risk, market risk, etc. The credit risk of mega infrastructure construction is reflected in the fact that the fund supplier of the mega infrastructure construction project can fulfill the guarantee to provide a sufficient fund flow for the project's construction as scheduled. Financial risk refers to the risks caused by the changes in the macroeconomic conditions, such as interest rates, exchange rates, and inflation. Market risk is reflected in the demand risk of mega infrastructure construction or its profit risk, and the occurrence of such risk originates primarily from changes in demographic structure, competition of similar projects, and adjustments in national policy.

7.3.3.3 Differences Between Mega Infrastructure Construction Finance and Mega Infrastructure Construction Investment and Financing

One of the necessities when proposing mega infrastructure construction finance as a scientific problem is to compensate for the deficiencies of the economic property of mega infrastructure construction investment and financing, and as such, it is a higher-level scientific term in that it combines such key words as mega infrastructure construction, investment and financing, and systems. Mega infrastructure construction finance not only includes the contents of mega infrastructure construction investment and financing in its connotation, but it also has more profound extensions. The differences between mega infrastructure construction finance and mega infrastructure construction investment and financing can be divided into four aspects.

1. Different academic levels

Mega infrastructure construction investment and financing is an intuitive name for the investment and financing activities of mega infrastructure construction. It is only a scientific term at the scientific concept level, and hence, it is not upgraded to the level of scientific theory. Compared to mega infrastructure construction investment and financing, *mega infrastructure construction finance is further sublimated to the scientific connotation of mega infrastructure construction investment and financing, thus forming a complete scientific system in which not only are the investment and financing activities at the mega infrastructure construction level included but so, too, are the components, relevant structures, organization modes, specific functions, operational methods, and business types of mega infrastructure construction.* From the perspectives of system design, institutional arrangement, and overall planning and management, mega infrastructure construction finance is a more fundamental and important scientific problem compared to mega infrastructure construction investment and financing. In addition, mega infrastructure construction finance has a specific development background, such as the recent establishment of the Asian Infrastructure Investment Bank.

2. Different connotations

Mega infrastructure construction investment and financing includes connotations in two dimensions, namely, investment and financing. The investment of mega infrastructure construction refers to the estimation process around the fund input and output of mega infrastructure construction, whereas the financing of mega infrastructure construction refers to the process of fund collection around the mega infrastructure construction. Mega infrastructure construction finance is the joint result of the constantly emerging mega infrastructure constructions and the important adjustment of the global public product financing pattern. As a new concept, this differs from mega infrastructure construction investment and financing and suggests that the connotation of mega infrastructure construction investment and financing is a series of financial and technical contents that include the project fund estimation, cost performance analysis, money flow budget, and analysis of the reliability of the funding source, whereas mega infrastructure construction finance has a stronger theoretical connotation. The connotations of mega infrastructure construction investment and financing involve a series of operational contents that include investment estimation, cost-benefit analysis, cash flow budget, and a reliability analysis of the funds of mega infrastructure constructions. Furthermore, mega infrastructure construction finance is the result of the emergence of mega infrastructure constructions and the global adjustment of public infrastructure projects, a new theory that departs from the traditional project investment and financing concept. At the same time, mega infrastructure construction finance is a complicated system composed of a complex subject and its own specific functions and the forms. Accordingly, mega infrastructure construction finance has a strong theoretical connotation.

3. Economic attributes

Analyzed from the perspective of economics, mega infrastructure construction investment and financing has economic effects in three specific areas, namely, features of quasi-public products, economic externalities of investment, and the macroeconomy. Thus, the economic effect of mega infrastructure construction investment and financing is analyzed from each of these three perspectives, but the analysis is greatly limited as reflected by the lack of deep cognition regarding the two key terms, i.e., investment and financing and project investment and financing. Mega infrastructure construction investment and financing is a compound scientific term, and the economic understanding of this scientific concept begins with the understanding of mega infrastructure construction and investment and financing. However, the existing analysis of mega infrastructure construction investment and financing focuses more on mega infrastructure construction as an object while ignoring the definition of the economic scope of investment and financing. As mega infrastructure construction finance is a scientific system consisting of the connotations of mega infrastructure construction investment and financing, the scientific system could expand on the many scientific problems. Moreover, mega infrastructure construction finance is an independent scientific term given its economic attributes.

4. Different structure functions

Different from mega infrastructure construction investment and financing, which center around the investment and financing of mega infrastructure construction, mega infrastructure construction finance is not only a series of financial activities that involve the fund financing, scheduling, arrangement, and management, but it is also a form of institutionalized arrangement with specific structure features, basic functions, and organizational and operational forms. The specific performance of the system structure with respect to mega infrastructure construction financing not only consists of an investment structure and financing structure, but it also contains the mega infrastructure constructions of capital structure, governance structure, and the external environment. In this sense, the content of mega infrastructure construction finance is richer than that of mega infrastructure construction investment and financing. In terms of organizational operations, financial engineering comprises organizational behavior, the contract system, risk aversion, and the post-evaluation of mega infrastructure construction problems. Compared to mega infrastructure construction investment and financing, mega infrastructure construction finance has greater influence on and is more involved in the organization, structure, and function of mega infrastructure construction.

7.3.4 The Organization and Structure of Mega Infrastructure Construction Finance

From the perspective of systematic science, mega infrastructure construction finance is a relatively independent complex system that constantly produces and engages in resource exchanges with the external environment. Thus, because it has its own structure features, organization, and operation forms, it is important to separate out the financial organization and structure of the major projects.

7.3.4.1 The Organization of Mega Infrastructure Construction Finance

Mega infrastructure construction is a complicated system that involves many participants including organizers, investors, financial institutions, consortium consultants, technical experts, contractors, suppliers, the public, etc. The different players in the major projects have different responsibilities and different concerns with respect to the financial system. Sorting out the relationship among the various bodies is a primary issue when solving financial concerns and organizing major projects (Car-Pušić 2014; Fan 2005; Kayser 2013).

1. Government

   As the initiator, approver, and decision-maker of mega infrastructure construction, the government plays an important role in mega infrastructure construction finance. First, the government guarantees the investment and financing environment for mega infrastructure construction finance; second, the government offers legal and policy support for mega infrastructure construction finance; third, the government provides powerful logistical support for mega infrastructure construction finance; and fourth, the government is able to bear certain project risks.

2. Investor

   The investor is the subject who signs the mega infrastructure construction contract with the government or the leading project companies. The investor can be a single company or a combination of several companies. In practical mega infrastructure constructions, the joint venture has become one of the major organizational forms as the organization can exploit its participation in the venture. In the operation process of mega infrastructure constructions, the investors do not directly complete the construction of the mega infrastructure construction, but rather, they establish an independent limited liability company according to their respective capital contribution, i.e., a project company. The capital from investors constitutes the project funds, and the project profits are distributed according to the proportion of the capital put up by the investor.

3. Financing party

The financing parties of mega infrastructure construction include, primarily, commercial banks, export credit agencies, multilateral financial agencies such as the World Bank and the Asia Development Bank, and nonbank financial institutions such as loan and trust companies. According to the differences in the project scale and the financing demands, the financing parties could be one or two financing agencies or a bank consortium formed by several banks or institutions. At present, various funding industries have been established by the local government to support and finance the development of mega infrastructure constructions.

4. Contractor

In mega infrastructure constructions, the contractor is the one primarily responsible for the project, and as such, he usually signs lump-sum contracts that specify fixed prices and fixed durations with the construction companies. Because the contractor is in charge of the project, the selection of the contractor is a key factor in influencing the success or failure of the project. The technical level, qualifications, credit, and financial ability of the contractor can affect the commercial evaluation and risk judgment of lenders to the project. Thus, the contractor impacts the likelihood of investors lending money for the project.

5. Supplier

For some projects, the timely, adequate, and stable supply of raw materials is of vital importance to the established construction timeline of the projects. Thus, the raw material supplier is one of the important participators in the mega infrastructure construction project. To ensure the steady supply of materials, the project company usually signs a long-term strategic supply agreement with the suppliers.

6. Professional operator

According to the operation characteristics of different projects, the project companies will sometimes hand over the operation and maintenance of the construction to professional operators. However, due to the differences in risk assignment, the operators' qualifications and the nature of the construction itself, professional operators will undertake different tasks and bear different risks in different projects.

7. Insurance company

Mega infrastructure constructions face many unpredictable risks during the construction of the project and the various operation periods. Therefore, the project companies, contractors, suppliers, and operators generally carry insurance to cover the various risks that they faced and to further disperse and transfer those risks. Meantime, because severe economic loss may result if the construction risks materialize, mega infrastructure construction companies should hold insurance companies to high standards regarding credibility.

8. Professional institutions

To avoid possible financial, legal, and human risks as well as risks associated with environmental protection and policies in mega infrastructure construction, the project company should employ professional third-party institutions, such as consultancy agencies or experts in financial, legal, taxation, insurance, and technical fields, as technical consultants to assure the ordered implementation of the mega infrastructure construction contract.

The financial organizations of mega infrastructure constructions, in addition to focusing on the organizational behavior of the company, they must also focus the overall procedures and practices of the organization. When investors obtain the appropriate qualifications for the construction of the project, they often assume the form of the project company when conducting their work. According to the size of the project, the interests of the investors' demands, the degree of recognition of the local government, and the characteristics of the source of the funds, the project company also assumes various organization forms and practice that may be based on the contract with the joint venture companies, the type of joint contract, the equity joint venture, or the trust fund types. During the process of building the project company, it is necessary to account for project fund audits, equity dispersion degrees, tax breaks, diversification advantages, and the subsequent transfer of assets to establish the most appropriate project company organization form.

In addition, the financial system of mega infrastructure construction involves many participants and many types of complicated relationships. Therefore, to protect the interests of the parties and the project construction, it is necessary to regulate the rights and functions of the parties as well as the corresponding mechanism of risk aversion. For example, government departments and investors, i.e., the project company, must sign an investment agreement or contract, loan contracts must be signed by the financial institutions and the investors, and a warranty contract and a first to purchase contract must be signed by investors and builders. Additionally, there may also be builders' contracts, leasing contracts, charter contracts, product purchasing contracts, and disclaimers that require signing by various subjects from among the many institutions and parties involved. The many series of contracts are not only required by each participating body, but they also serve as the basis risk problem solving.

7.3.4.2 Structures of Mega Infrastructure Construction Finance

The organization of mega infrastructure construction finance includes the subjects, organization forms, and contract system. The structure of mega infrastructure construction finance is based on the relations among and between the subjects and the contracts. There are four structures in mega infrastructure construction finance: capital structure, investment structure, finance structure, and governing structure.

1. Capital structure of mega infrastructure construction finance

The capital structure of mega infrastructure construction finance determines the share of capital funds and the liability fund forms of the project, the proportional relationship between them, and the corresponding sources. In mega infrastructure construction finance, the project capital structures that should be adopted include capital stock, loans from commercial banks or policy banks, loans from international banks, bonds, and industrial trust funds. Therefore, the ratios of the sources of funds, i.e., equity capital to debt capital, domestic capital to international capital, and business loans to interest-free loans, should be fully considered to minimize capital financing costs and optimize capital structure under the condition of capital availability.

The key to optimizing capital structure is institutionalized management. The institutionalized management of the mega infrastructure construction fund involves three factors. First, the management of the mega infrastructure construction fund with respect to the financing process refers to the contract system design and involves a multiparty interest relationship and the corresponding legal effects; second, the management of the collective fund for mega infrastructure construction and operational purposes, including financial management, cash flow management, and financial auditing of the mega infrastructure construction fund; and third, the optimization of the fund structure, capital structure, and equity structure of mega infrastructure construction as well as the control of construction costs.

2. Investment structure of mega infrastructure construction finance

The investment structure of mega infrastructure constructions refers to the legal provisions granted to the mega infrastructure construction investor regarding rights and interests to project assets, the legal partnership among the project investors, and the ownership structure of mega infrastructure construction. The major components of the investment structure include property rights responsibilities of mega infrastructure construction, decision-making procedures, liability responsibilities, cash flow, taxation structure, and accounting procedures, among others. There are investment structures and frameworks for project investment available from international and domestic project practices. These include company joint venture investment structures, compact structures, partnership joint structures, and the trust fund investment structures.

3. Financing structure of mega infrastructure construction finance

The financing structure is the core of fund financing with respect to mega infrastructure construction finance. The scientific and reasonable financing structure should be optimally designed and selected to satisfy the targets and needs of the investors and other parties who have a financial interest in the project. The different financing plans, implementation processes, and management behaviors of the working entities engaged in the construction project should be detailed in the design of the project financing structure. At the same time, a financial analysis of the project should be considered during the financing process. Accordingly, the financial staff should have professional technical knowledge regarding the financing mode, sources for financing, financing, and a financing project market to broaden the financing channels, reduce the cost of financing, and solve problems that may occur during the financing process (Pederson et al. 2006; Wang 2009).

In addition, the capital reliability of the mega infrastructure construction project should be a primary focus. Reliability refers to the degree of reliability of the source of the project's funding. The reliability analysis requires the initiator of the mega infrastructure construction project to clearly recognize the costs and expenses of the project construction, predict the possible risks and cost overruns, assess the possibility of duration extensions, sign the relevant contract forms with banks and other funding sources, and avoid such conditions as non-availability of funds, project delays, and even project abortion due to emergencies. More specifically, the capital demand of mega infrastructure constructions is huge, and therefore, it cannot be provided by a department, bank, or enterprise. Rather, it requires the combination of multiple departments, a national bank, and/or a consortium of joint funds to meet a project's financial demands. Therefore, a feasibility analysis of mega infrastructure construction is an essential link for mega infrastructure construction financing.

4. Governance structure of mega infrastructure construction finance

The governance structure of mega infrastructure construction finance refers to the institutionalized restrictions and the coordination of the mega infrastructure construction finance system. Many factors are involved in the system of mega infrastructure construction finance, such as commercial banks, multinational investment banks, policy banks, insurance companies, industry funds, guarantee agencies, and enterprise consortiums. The governance structure of mega infrastructure construction finance refers to the institutionalized restriction and coordination of the mega infrastructure construction finance system, and as such, it is comprised of many stages including the design of the financing mechanism, the signing of the financing contract/s, the management of the financing fund, etc. Regarding the numerous interested subjects and participation procedures, avoiding possible violations and conspiracy and rent-seeking behaviors in each link, avoiding the overuse and inappropriate use of capital resources, and avoiding other similar problems form the main content of the mega infrastructure construction finance governance.

7.3.5 Scientific Problems of Mega Infrastructure Construction Finance

The background, scientific connotation, and structure of mega infrastructure construction finance have been detailed and discussed as an academic definition of mega infrastructure construction finance. However, as a new science ideology and scientific problem, the definition and connotation of the concept are not sufficient. Rather, more academic value and practical value of scientific problems should be proposed as doing so, according to the practical theory of mega infrastructure construction in China, will put forward several scientific problems. That said, these problems constitute only a discussion point about mega infrastructure construction finance, and thus, researchers should focus more on serious academic problems.

1. The financial evaluation of mega infrastructure construction

The financial evaluation of a project involves a comprehensive comparison and judgment process that is based on expected goals. This process applies scientific and normative methods and identical evaluation standards to evaluate the economy and the efficiency and effectiveness of the process and the results of investment and financing. Furthermore, this process scientifically, objectively, justly, and thoroughly controls and supervises feedback regarding the financing of the construction process with respect to mega infrastructure construction, and it maximizes the efficiency and effectiveness of mega infrastructure construction. The evaluation of the project's performance involves an inspection and assessment of the implementation process, the economic benefits, the sustainability of the project, the risk problems associated with the project, overflow influence, etc. to confirm whether the financing process and fund use are in the predictable range and then to provide references for follow-up work or for other similar projects through timely and efficient information feedback (Byoun and Xu 2014).

The post-evaluation is also an important part of the whole evaluation process of mega infrastructure construction because it aims to assess the financing operations of mega infrastructure construction and, therefore, to evaluate, thoroughly and systematically, the financing process. During the post-evaluation process, several factors are included, such as the evaluation agent, evaluation object, evaluation content, evaluation criteria, and evaluation mechanism. One of the most important problems, however, is how to design and develop this content within the system of mega infrastructure construction finance to ensure that the capital can be allocated during the building and operation process of mega infrastructure construction.

2. Investment and financing decision-making and mode selection

The investment and financing decision-making and the mode selection of investment and financing are problems that confront mega infrastructure construction finance (Cheng et al. 2011; Eweje et al. 2012).

Among the scientific problems confronting mega infrastructure construction finance, the first is the economic evaluation of mega infrastructure construction, such as choosing a reasonable evaluation method, predicting financing data, measuring the benefits and costs, and analyzing the effect on the economy.

The second is the design and selection of investment and financing schemes, which means designing and selecting the best investment and financing scheme according to the various project types. Because mega infrastructure construction projects can be divided into many categories such as traffic projects, hydraulic projects, and public facilities' projects, it is crucial to match the project with a reasonable investment and financing scheme.

The third problem is related to the project investment fund and cost control. The project investment fund and cost control, as aspects of mega infrastructure construction, change constantly according to the macro environment and the building process. Therefore, it is important to adjust investment amounts, control costs, and maximize efficiency.

The fourth issue involves the mode selection of investment and financing. Expanding the financing channels to include both public and private and amplifying the private sector's investment in mega infrastructure construction are important in mega infrastructure construction finance. The introduction of private sector investment not only increases the amount of available funds, but it also strengthens project management and controls investment risk.

3. Risk analysis and avoidance in mega infrastructure construction

Risk is one of the major topics in the literature about mega infrastructure construction management. Thus, with respect to mega infrastructure construction finance, the analysis of financial risk and the avoidance of financial risk are important factors. The risks in mega infrastructure construction are divided into three types: country risks, market risks, and project risks. Country risks are those risk factors that impact politics and macroeconomics, trade rules both at home and abroad, and volatilities in price and rate. Market risks include project building technology, scarcity of resources, policy support from local governments, and agreements with local residents. Project risks refer to risks associated with the design, building, supply, quality control, and operations of the project (Wu and Wei 2009).

In addition, with respect to mega infrastructure constructions, the risks can be assigned to one of two categories, namely, financial risks and investment risks. The first is the financial risks of investment projects include the interruption of infrastructure construction projects, insufficient liquidity of the borrower or the lending country's government, and the failure of the financing party to achieve rolling financing. The second includes investment risks caused by noneconomic factors such as political, military, and safety issues. For example, political issues, such as changes in the government, increase investment risks; military issues, such as geopolitical conflicts and military confrontations, cause engineering paralysis; and safety issues, such as threats by extremists and terrorism activities, result in increased investment risks.

4. Control of financing in mega infrastructure construction

In the framework of traditional project investment and financing, some unilateral standards were generated during the process of financial evaluation and budget control. Among these standards are budget estimation, budget approximation, budget settlement, and settlement evaluation. According to these standards, it is necessary to consider how to improve the budget system in mega infrastructure construction finance and avoid/prevent out-of-control investments, budgets, and finance management (Lu et al. 2015b; Priemus et al. 2008).

With respect to the mega infrastructure construction finance system, the project's financial budget has specific functions, namely, to ensure the safety and security of the construction fund, guarantee the reasonable distribution of the financial budget, and provide support for other goals, such as the progress and quality of the construction, in mega infrastructure constructions. Budget control during the construction process of mega infrastructure constructions is divided into three stages, specifically, the earlier stage, mid-stage, and later stage. The earlier stage involves the control of the preliminary budget, the mid-stage involves the control of costs, and the later stage involves the control of the entire budget. Accordingly, the financial budget control system of mega infrastructure construction includes several elements. Among these elements are the use of money as outlined during the construction planning, the scheduling of construction and related investments, and the decisions regarding investment control, investment budget adjustments, safety assessments of funds, and the financial budget itself. These elements, combined with the investment and financing decisions and patterns, form a financial budget control communication and feedback system in mega infrastructure construction.

5. International integration of mega infrastructure construction

On June 29, 2015, an agreement with the Asian Infrastructure Investment Bank was formally signed in Beijing. This agreement signified the formal establishment of the Asian Infrastructure Investment Bank (AIIB). As a multilateral development institute of intergovernment property, the AIIB is the first professional, regional, and quasi-commercial infrastructure investment bank in the world. As such, it is committed to infrastructure construction not only in Asia but throughout the world (Aneja 2014; Choe 2015). From the perspective of operations, the gap in infrastructure construction capital is addressed by the combination of bank loans, trust funds, and public-private partnerships. The major investment field of the AIIB is infrastructure projects, and the investment in infrastructure projects always requires the relevant institutions to exhibit strong project operations and management experience and a deep understanding of international financing. It can be said that because of the emergence of the mega infrastructure construction trend and the establishment of the AIIB, the mega infrastructure construction financing system has been perfected, resulting in the emergence of mega infrastructure construction finance. With the development of the AIIB, a number of practices and scientific issues related to mega infrastructure construction finance will be encountered and solved and thus enrich the mega infrastructure construction finance theory.

7.4 Technology Management in Mega Infrastructure Construction

Construction refers to those activities in which humans create artificial entities based on certain scientific and technological principles and natural rules under the direction of certain human intentions (Encyclopedia Britannica Online 2016). Thus, capital, talent, and technology constitute three significant foundations and pivots of the construction projects. This is particularly prominent with respect to mega infrastructure construction. First, mega infrastructure constructions require complex technologies; second, these technologies may have the “a little leak will sink a great ship” effect on the cost, quality, process, and security of constructions, which means, a slight move in one area may affect the situation as a whole; and third, the construction subjects of a project are often lacking in sufficient technological preparation, which may result in a conflict whereby the demand for engineering technologies cannot be met because of insufficient technological supplies, thus hindering the smooth development of the construction process. From this perspective, it is safe to say that, to some extent, technology is the core element of mega infrastructure construction, and thus, the management of technologies becomes one of the core activities in the management of mega infrastructure construction.

7.4.1 Overview of Technology and Technology Management in Mega Infrastructure Construction

In general, mega infrastructure construction technologies refer to all of the technical crafts, methods, skills, and means that humans have achieved based on their accumulated experiences and knowledge gained regarding the long-term construction practices and principles of natural sciences. Mega infrastructure construction technologies should be perceived as a technological system aimed to support and ensure the completion of constructions rather than as a single set or as several sets of technologies. Mega infrastructure construction technologies have several connotations and are categorized into several types:

1. In terms of the integrity of the demands in entity-creating construction activities, mega infrastructure construction technologies include both the construction technologies required for building the physical entities of a construction project and the management skills necessary to ensure that the various entity-creating construction activities will be performed effectively and systematically. Accordingly, this requires not only the hard construction technologies, such as the construction crafts, methods, approaches, advanced materials, and equipment, but also the soft management skills, such as an effective management system, organization process, and management methods.
2. Mega infrastructure construction technologies, regardless of whether they are hard technologies or soft skills, involve multiple areas and disciplines, such as civil engineering technologies, mechanical engineering technologies, information technologies, and automation technologies.
3. From the perspective of hierarchy, mega infrastructure construction technologies can be generally categorized into three types.

The first is general technology, which is often used in routine construction activities. Technologies of this type are usually mature and relatively simple, and thus, people have already mastered these technologies.

The second, improved technology refers to those technologies that have been improved based on the unique features of specific constructions or new technical standards. For the most part, humans have already acquired the basic principles of these types of technologies, but they require further training and improvement mastering these technologies.

The third type is breakthrough technology (Kelley et al. 2013), which refers to the technologies for which the basic principles are unclear and the processes are not yet confirmed or to those technologies that humans have not yet mastered yet due to the Great Leap Forward development and the complexity of the constructions.

Technologies of this type usually cannot be achieved through simple integration or the improvement of existing technologies. Rather, technological innovation is required to achieve breakthroughs or a huge advancement in technological thresholds.

The latter two types of technologies, especially the breakthrough technologies, have a critical bearing on the success of mega infrastructure constructions. The technical thresholds include technological principle thresholds, material performance thresholds, and equipment function thresholds. Regardless of the perspective, the relationship between the difficulty to achieve breakthroughs in these thresholds and the complexity of mega infrastructure constructions is usually nonlinear, which means that the increase in difficulty to gain technological breakthroughs exceeds the increase in the complexity of the construction. Thus, it is inevitable that contradictions between the demand for critical technology and the serious lack of technological supply in the process of mega infrastructure constructions will be encountered. In general, the main reasons for the lack of technological supply include the uniqueness of the construction environment and the construction scheme, the absence of mature technological preparation, the unavailability of similar alternative technologies both at home and abroad, the technological monopoly (Locatis 1994), and the excessively high technology transfer prices.

Table 7.5 presents a list of necessary critical technologies provided in the initial construction phase of a mega cable-stayed bridge construction project and the descriptions of the supply of technologies in this phase (Sheng 2009). The project was executed in China in the 1990s with an investment of several billion RMB. Table 7.5 reveals that the short supply of technologies is common in the process of mega infrastructure constructions, a situation that requires serious consideration and an effective solution.

In general, resolving the conflict between the pressing technology demand and the insufficient technology supply in mega infrastructure construction requires integral technology management activities. For example, issues such as organizing and establishing innovation platforms and designing technological innovation routes in the process of innovating and inventing mega infrastructure construction breakthrough technologies and making technological decisions that set technological standards and establish technological organizations and systems have significant technology management connotations. Therefore, they are of great importance to the selection, integration, and implementation of mega infrastructure construction technologies.

In conclusion, technology management in mega infrastructure construction is referred to as technological decision-making and selection, technology allocation and integration, and planning and coordination of technological resources. Furthermore, the organization and management activities are conducted with a focus on technology supply and technology support in mega infrastructure constructions in light of both mega infrastructure construction technological innovation and technological applications and the mechanics of mega infrastructure construction technological activities.

The proposing of the concept of technology management in mega infrastructure construction management theories has significant theoretical value as well as practical meaning.

Table 7.5 List of technologies needed for a bridge construction project

Number	Critical technologies	Present situation of technology supply	Technology supply in China
1	Main bridge structure system studies	Foreign normative design standards focus on suspension bridges, whereas design standards in China apply to cable-stayed bridges with smaller spans	No design standards or norms could be referenced for the construction of cable-stayed bridges with spans over 1000 meters
2	Wind-resistant performance studies	The main research means are numerical simulations and wind tunnel tests	Current tests lack three-dimensional analyses of aerodynamic instability mechanisms of mega cable-stayed bridges and reflect complete refined theory of wind loads on mega cable-stayed bridges
3	Seismic performance studies	There are two types of seismic designs for use at present: Ductile seismic design and seismic isolation and reduction design	Cannot directly reflect the structural performance or degree of damage; lacks site seismic effect analysis of mega cable-stayed bridges constructed in thick, compact, soft, or weak soils; lacks standards for seismic designs
4	Collision avoidance system studies	The AASHTO of the USA has a comprehensive guide of specifications and new technologies, such as the VTS system	Study results of large shapes based on existing technologies deviate seriously from actual situations
5	The design and construction of a great pile group infrastructure	The current largest pile has a length of more than 120 m; the largest pile has a diameter of more than 3 m; the bearing capacity of a single pile can reach 12, 000 tons. Most piles are constructed using cofferdam construction technology	The existing pile foundation standards are not entirely suitable for the design of cast-in-place piles with mega diameters
6	The design and construction of scour protection	There are many studies of construction technologies and processes for scour protection that have resulted in the forming of construction standards	Currently, China lacks projections of partial scouring on the base areas of complex pile groups under the effect of two-way tidal streams; domestic construction technologies and processes regarding underwater throw protection cannot be used to guide the engineering design and construction of pile group pier scour protection in estuary areas

(continued)

Table 7.5 (continued)

Number	Critical technologies	Present situation of technology supply	Technology supply in China
7	The design and construction of super-high steel-concrete composite bridge pylons	Significant progress and developments and have been made in technologies, such as the control of the height and shape of the bridges both at home and abroad	Currently, there is no approach in China to apply the steel anchor box schemes commonly used in other countries, and there is no approach to apply advanced information technology and computer software technology in bridge tests
8	Cushion technology for extra-long, cable-stayed bridges	Broad studies have been conducted that focus on various vibration types at home and abroad; corresponding measures have been developed	Some theoretical research achievements need to be improved and perfected as applied in construction practices
9	Girder erection technology	The largest abroad floating crane has a weight of more than 4000 t and a lifting height that exceeds 100 m	The capacity of construction equipment in China must be enhanced; the deck derrick crane calls for further research and improvements; he hoisting weight in China still lags behind those in other countries
10	Construction control technology	Computer control technologies for automatic tests, analyses, and forecasts have been developed in other countries. By achieving technological upgrades in the remote monitoring of sensors and bridge structures, the health monitoring of the bridge structures and the evaluation of the safety system are substantially improved	China started late in this area, and domestic studies of the construction control theory are still insufficient, with backward control measures and insufficient forecasting and judgment accuracies. A comprehensive construction control system has not yet been established

With respect to general engineering constructions, the construction technologies are, for the most part, common and mature, and thus, people have already mastered the principles of these technologies, and the standards and processes regarding how to use and manage these technologies in construction practices have been well developed and established. As a result, technology management is not a salient problem in the traditional project management knowledge systems. Therefore, it is understandable that in the PMBOK, management knowledge is divided into nine areas (Project Abdul-Rahman et al. 2013) and that technology management is not recognized as one of these nine areas. However, with respect to mega infrastructure constructions, not only are the importance and critical functions of technologies prominent, but the complexities, connotations, risks, and uncertainties of technology management have far surpassed those of general constructions. Additionally, they all have a great influence on and provide guidance in other areas of mega infrastructure construction management. For example, to use a new technology that has certain defects in basic principles may add great difficulty to the site construction work and result in potential construction quality problems and extensions of construction periods. Moreover, in circumstances where the mega infrastructure construction supply can only be satisfied through technological innovations, the problems are much more complicated because, in these circumstances, the management subjects of the construction project must establish the innovation platforms as well as the design platform mechanism and processes, and they must successfully allocate and integrate the technological innovation resources. Because this is essentially an action to generate technological innovation capacity by designing a complicated management system, mega infrastructure construction management not only has an effect on integration management, procurement management, time management, cost management, quality management, human resource management, communication management, and risk management in the design and construction processes, but it also impacts operation risk control and efficiency control in the latter periods of the construction. Therefore, introducing the concept of technology management into the mega infrastructure construction field not only perfects and enriches the knowledge system of mega infrastructure construction management, which could improve people's control of construction technologies, but it also has a great positive influence on promoting the development of the theoretical system of mega infrastructure construction management.

Therefore, in terms of mega infrastructure construction management, it is necessary to develop technology management as a new and important management area. In other words, from the perspective of the knowledge system, the PMBOK of mega infrastructure construction must be extended to include technology management as the tenth knowledge area.

7.4.2 The Selection of Technologies in Mega Infrastructure Construction

1. The Definition and Connotation of Technology Selection in Mega infrastructure construction

The core of mega infrastructure construction technology management is the selection of technologies to be used in the constructions. *The concept of construction technology selection is referred to as the process of determining and implementing the technological schemes created for mega infrastructure construction tasks through scientific procedures.*

First, the primary design of a mega infrastructure construction involves the specification of the structures and functions of the hard system for entity-creating construction. Design schemes provide the construction basis for the project and determine the overall functions and quality of the project. Accordingly, the construction design, which includes the selection of major, complex technology schemes, has a critical bearing on mega infrastructure construction. Therefore, technology selection is a comprehensive and instructive step for mega infrastructure construction activities.

Second, the technology selection with respect to mega infrastructure construction does not refer to the selection of one or two specific units of technologies. Instead, it is the selection of technology groups based on the overall needs of a certain construction project and on the supply of a series of technologies and knowledge according to the varied demands of the construction process. In addition, technology selection is not based solely on comparisons of multiple technologies from the perspective of technical advancement. In fact, technology selection requires that people consider technology a key factor in the design schemes of construction and that they select the technology scheme based on the overall evaluation and comparison of the different design schemes. In other words, the properties of a certain technology, such as the advancement and maturity of technology, should be evaluated systematically along with its contribution to the entity-creating construction process and with respect to economic efficiency, security, and quality assurance of the technology.

Third, the technology selection in mega infrastructure construction has salient features, i.e., it is partially modifiable and irreversible as a whole. According to the basic procedures of project constructions, the technology selection in mega infrastructure construction is conducted during the construction design phase of the primary construction period. The design schemes for the construction formed in this phase not only establish specific requirements for the overall function, structure, construction period, and quality of a certain construction project, but they also establish the rules for the selection and determination of solutions for major complex technological problems that occur during the construction process. In other words, the construction design scheme developed during the primary period of a mega infrastructure construction has determined the basic principles, engineering technological rules, and comprehensive efficacy and functions of mega infrastructure construction technologies. Moreover, this determination has become a part of the hard system of construction, and as one of the basic factors, it has been solidified, thus allowing the technology selection to have sustained and important functions throughout the life cycle of the construction. In construction, the success on the first try philosophy and the continuous evolution of the construction process are highlighted, which means that once the mega infrastructure construction technologies are determined, despite subtle and fine modifications and improvements, the technology selection is irreversible. Since critical technology selections must be made during the scheme design phase of the construction, technology selection is an immediate and complex management behavior that calls for long-term effectiveness. Therefore, technology management activities that fully reflect the behavioral characteristics of the technology selections in mega infrastructure construction are required as a guarantee.

2. Principles of Technology Selection in mega infrastructure construction

Theories and experiences have proven that the basic principles of technology selection in mega infrastructure construction are as presented herein.

(i) The technology to be selected must be extensible in its connotations. Mega infrastructure construction technologies usually have rich connotations. Thus, in addition to having solid scientific principles as their foundations, such technologies should have the ability to develop new construction schemes and technologies, the ability to create new critical equipment for the construction of new technologies, or the ability to form new construction materials based on scientific principles and thus become a necessary pillar for the construction of project entities.
(ii) The technologies to be selected must be integrated into the construction. Mega infrastructure construction technologies are the instruments and tools derived from the engineering thinking focused on the success of the entity-creating activities. The value and significance of such technologies are reflected in facilitating the engineering creation of entities, and thus, to achieve this, the selected technologies must be able to be integrating into the construction. Thus, the selection of important complex construction technologies must be based on the premise that the fundamental principles are correct. Once this is established, the necessary engineering load tests, model tests, full-scale tests, and field tests as well as the required laboratory tests, intermediate tests, and pilot tests are requisite intermediate links and processes that cannot be ignored. Accordingly, it is necessary to obtain real information and data according to the actual demands in the engineering field and then to continue to revise and perfect the technology schemes until the schemes can be applied in the field. After multiple repetitions of this process, the technology risks are minimized, and the feasibility and reliability of the technology scheme are ensured and improved. For instance, the selection of the critical technologies for the construction of subsea tunnels calls for full-scale model tests of the immersed tube segments and the verification of the reliability of different concreting technologies, concrete mix designs, and cracking control techniques through multiple real sampling.

3. Routes for the Technology Selection in Mega Infrastructure Construction

The technology selection in mega infrastructure construction is a complex systematic project. First, it involves technologies from disciplines; therefore, it needs to integrate these technologies to form and develop a new overall technological capacity. Moreover, the technologies to be selected should be able to exert practical effectiveness and should be able to be transformed into operational construction schemes and new equipment, new materials, and new processes while exhibiting low controllable risks and costs. Therefore, besides using a series of scientific approaches such as qualitative and quantitative measures, experimental simulations, and computer simulations of the technical aspects of the selection of construction technologies, people also need an effective working mechanism and organization support when selecting the technologies. The following factors should be considered during this process:

(i) The selection of mega infrastructure construction technology is a group decision (Davis et al. 1982). The group should include construction experts, technologists, construction management experts, and professionals from areas such as sociology, environmental science, and finance as well as experts from institutions and organizations responsible for construction design, contracts and consulting. Furthermore, this group should have the capacity to evaluate the technological principles, the technical feasibility and the technical practicability and the capacity to conduct scientific analyses of the economic efficiency of the technologies and the technological risks.
(ii) The technology selection calls for necessary support platforms, such as a relevant database and model base, methods for analyzing the economic efficiency, and support systems for the comprehensive assessment of the technologies.
(iii) The technology scheme selection is a group decision-making process, and the complexity of the constructions as well as the technologies suggests that individuals in the technology selection group may have their own understandings of different technologies and their personal preferences for different standards in selecting technologies. Thus, there will initially be non-consensus regarding the technologies. Whereas this is normal during the early stage, the group members will have to identify, refine, and correct the scientific and reasonable aspects of their non-consensus understandings and preferences by implementing certain working mechanisms. In other words, they must collaborate with each other and move from non-consensus to consensus (Hai et al. 2000). Only in this way can the final technology schemes they select be guaranteed to be scientific.
(iv) To improve the quality of their technology selections, in addition to the groups that directly participate in the technology selection, a technological advisory committee composed of experts with extensive technology management experience should be established to conduct independent reviews of the key schemes presented during the technology selection process.

By implementing organizational models and mechanism designs for technology selection, the technology scheme will be based on strong selection concepts and principles and will have the necessary backing of the organizations as well as support platforms at multiple levels and in various domains.

During the process of selecting the mega infrastructure construction technologies, people focused on maximizing the functions of group decision-making and allowed the experts to exploit their talents. Nonetheless, the complexity of the construction fields and the dynamic changes of the environments, especially the various types of deep uncertainties, affect the effectiveness and stability of the functions exerted by the selected technologies. Therefore, it is still necessary for people to establish technical standards for the technologies to be selected. In particular, the standards must be aligned with the technology schemes to gain the necessary reliability and robustness (Alippi 2014). Further, it is also necessary to develop a set of methods that can be used to improve and control the technology schemes, ensuring that the proposed can be realized effectively and stably during the construction process and the whole life cycle of the construction.

7.4.3 The Management of Technological Innovations in Mega Infrastructure Construction

Some parts of the technologies that are necessary for the implementation of mega infrastructure constructions are achieved by creating new technologies through technological innovations. This involves another important function in mega infrastructure construction technology management, namely, the management of technological innovations relevant to the construction. *The management of mega infrastructure construction technological innovations refers to those project management activities that are intended to organize and achieve technological innovations by providing management support to guarantee the implementation of mega infrastructure construction technological innovations (Jolly 1980).* Accordingly, technological innovation management is comprised of numerous factors.

7.4.3.1 The Strategic Choice of Technological Innovations in Mega Infrastructure Construction

Technological innovations in mega infrastructure construction involve the invention and creation of new technologies during the construction entity-creating process. It is a complete and complex systematic construction process that requires high-quality top-level design and strategic planning. A strategy is a long-term plan that outlines the activities necessary to realize the overall goals while considering the whole situation and the long-term objectives. The selection of innovation strategies is not determined through specific working procedures and processes; rather, it requires a comprehensive plan of the innovation goals, principles, positioning, and guidelines at the macro level. As such, the plan assumes a leading and guiding role throughout the entire construction process.

Given the features of mega infrastructure construction entity-creating activities and the functions of the technological innovations, the strategic choice regarding technological innovations in mega infrastructure construction includes the following points:

1. Construction-oriented and multiple support strategies

The purpose of technological innovation of mega infrastructure construction is to provide necessary technological resources for construction entity-creating activities through scientific innovations, inventions, and creations. The most salient feature of mega infrastructure construction technological innovation is construction demand oriented. Because the innovations with respect to mega infrastructure construction technologies face great difficulties and require major breakthroughs, people must not only establish effective innovation platforms, but they must also receive supports from other academic and consulting institutions. Furthermore, they may need to integrate domestic and foreign resources to expand and strengthen their innovation capacity.

2. Multilayer innovation strategy

In recent years, with the constant expansion of mega infrastructure construction scales and the increase in technological complexity, construction-oriented technological innovations have encountered increasing technological problems at various levels, including the construction, industry, national, and global levels. Therefore, we have developed a multilayered strategy that is consistent with national strategies for technological innovation in mega infrastructure construction that is set in accordance with the construction orientation principle and with full consideration of the overflow effect (Aghion and Jaravel 2015) of construction technological innovations and industry innovation objectives. Accordingly, studies focused on tackling key scientific and technological problems now have a foundation from which to work as the values common in the construction industry have been defined and are based on the specific problems common in construction. These efforts will improve the levels of science and technology in the industry and enhance the country's competitiveness in the fields of science and technology. The multilayered strategy of technological innovation in mega infrastructure construction is comprised of three layers:

(i) The construction-level strategy involves the construction-oriented scientific and technological innovations.
(ii) The industry-level strategy involves the innovation of critical technologies that are commonly needed in the construction industry.
(iii) The national-level strategy involves innovations that have transcended construction-oriented innovations and industry-needed innovations and rises to the level of science and technology competition among different countries.

3. Innovation industry chain strategy

With the successful development and application of mega infrastructure construction technological innovations, it is necessary to develop the capacity to independently produce innovative products and promote the development of related industries, thus facilitating the extension from products to industries. Specifically, given the national scientific and technological innovation strategies and the effects of mega infrastructure construction on the country's social and economic development, there is a complete chain structure in mega infrastructure construction technological innovation, namely, construction technological innovation projects—technological innovations achieved—innovative products generated—industrialization.

Consider the Sutong Bridge in China as an example. High-strength zinc-coated wires measuring Φ7 mml 770 MPa with a low degree of relaxation are used in the stay cables, which are one of the key materials in building thousand-meter-long cable-stayed bridges. The owners of the project decided to stop buying the cables from foreign suppliers and designated Shanghai Baosteel Group Corporation to produce stay cables through technological innovation. After more than a year, they successfully developed new stay cables that have excellent torsion performance and have transformed from construction innovation project to product innovation.

All of the stay cables used in the construction of the Sutong Bridge, which totaled 6500 tons, were provided by the Baoshan Group, Corp. In all, 272 cables were used in the construction of the bridge, with the longest one being 577 m and having a quality of 58 t. The cables were designed to last for 50 years, which far surpasses the current requirements that stay cables should be able to last for 25 years. This not only represents great breakthroughs in the manufacturing of stay cables in China, but it also has driven the growth of this industry by successfully accomplishing the transformation from innovation technology in construction to innovative products (Sheng 2009).

4. Metasynthetic innovation strategy

Technological innovations in mega infrastructure construction involve not only ordered activities in the technical field but also call for well-organized management and coordinated activities that provide the necessary support and guarantees. Therefore, during the process of technological innovation, it is of great importance to design and plan necessary innovation management systems that thoroughly address the subject, platform, organization, rules mechanisms, etc. of innovation and ensure that such systems are well integrated with the technological innovation activities to form an integral, effective, and operational metasynthetic system (Qian et al. 1990). This very system should not only be able to provide support for and guarantee the technological innovation activities, but it also should be capable of regularizing and optimizing the objectives and functions of technological innovations and should avoid redundancy in innovation and unreasonable negative effects in areas such as construction costs, construction period, and construction safety and quality.

Furthermore, as a methodology to analyze and manage complex systems, the metasynthesis has great guiding and practical significance for complicated and systematic activities such as technological innovations in mega infrastructure construction. In particular, the combination of quantitative and qualitative analyses, human-machine integration, control and self-organizing control, consensus of community opinion, and comprehensive evaluation methods in the methodological system of metasynthesis, all have great importance in the practical and operational processes of technological innovation activities in mega infrastructure construction.

7.4.3.2 The Management of Technological Innovations in Mega Infrastructure Construction

The management of technological innovations in mega infrastructure construction is an integral system composed of several parts.

1. The selection of technological innovation methods in mega infrastructure construction

Before selecting certain methods for technological innovations in mega infrastructure construction, there are three major types of basic technological innovation methods with which one should be familiar:

(i) Inherited innovation (Gatignon et al. 2002). This refers to technological improvement and perfection based on the original technologies. Generally, it is achieved through improving the original technology in certain areas. This type of innovation can meet the current needs and guarantee the possibility of innovation at the same time.

(ii) Revolutionary innovation (Sen 2014). This type of innovation requires people to make certain changes and improvements to the original technologies. The functions in the original technologies are maintained, while the technologies are further optimized and promoted. Revolutionary innovations are the major forms of construction technological innovations. Innovations such as integrated innovation and innovation based on adaptation and assimilation belong to this category.

(iii) Disruptive innovation (Christensen and Snyder 1997). The disruptive property does not mean that the purpose of the innovation is destructive; rather, it refers to a certain type of original or even contrary innovation that disrupts the principle or development path of the original technology. Such innovation requires a long period from its initial proposition to its final verification, and it may require much more time for people to understand and accept this innovation before it gradually grows and matures in construction practices. It is evident from the features of technological innovations in mega infrastructure construction that not all technological innovation methods meet the construction requirements. For example, although originality can be best embodied in disruptive innovations, for the sake of stability and robustness of construction technological innovations, disruptive innovations are usually not selected as the major form of construction technological innovation. Therefore, taking into consideration the requirements that construction technological innovations should make breakthroughs while simultaneously keeping the risks low, inherited innovations, and revolutionary innovations are more acceptable.

Further analyses of the inherited and revolutionary properties of these two innovation methods indicate that they generally refer to technological extensions and improvements based on existing mature technologies and that they involve both the expansion of the technical application field and the improvement of the technical functions, which requires the combination and integration of technologies from multiple areas. This is consistent with the basic idea of meta-synthetic management. Therefore, technological innovations in mega infrastructure construction are mainly carried out under the strategy of "guided by demands, development with inheritance, meta-synthetic innovation, making breakthroughs at key points."

2. The building of a technological innovation platform in mega infrastructure construction

A technological innovation platform in mega infrastructure construction refers to the necessary conditions and environments for technological innovation activities formed through the selection of the innovation subjects, the determination of the behaviors and responsibilities of the subjects, and the design of effective operation mechanisms (Lubchenco 1998). Such platforms can form and bring forward the capacity to achieve technological innovations. This capacity is derived from the overall behavior of the innovation platform and reveals the overall functions of the platform.

1. The selection of innovation subjects

The primary task of technological innovation management in mega infrastructure construction is to build an innovation platform, and the selection of innovation subjects' functions as the foundation for building an innovation platform. According to the innovation theory of Schumpeter (Pol and Carroll 2006), innovation is the recombination of production factors. During the process of mega infrastructure construction and in consideration of the limited resources and capabilities, it is difficult for a single subject to integrate independently all of the factors needed for innovation. Therefore, the subject of mega infrastructure construction technological innovations is usually a union of owners, design units, construction units, colleges, scientific research institutes, among others. Together, they constitute the platform for innovation in mega infrastructure construction. Among these many subjects, different subjects supplement and complement each other with respect to functions and perform different, though indispensable, complementary roles in the technological innovation platform of mega infrastructure construction (Banker and Kauffman 2004).

In addition, as the objectives and environments of a construction project change, the constitution of the technological innovation subject exhibits certain flexibility (Nutt et al. 2010) that is reflected in the change of the constituents of the innovation subjects in different construction phases. For instance, in the construction design phase, the design units should be the primary innovation subject, whereas during the construction phase, the subject would be the construction units. Such flexibility allows the innovation subjects to generate the technological innovation capabilities that can best meet the construction requirements as the construction proceeds.

Many technical difficulties confronted during technological innovations in mega infrastructure construction can only be solved by relying on studies, such as mathematical, information, and hydrological, geological, and metrological studies. Moreover, many critical key technological studies involve the study and investigation of basic principles. These studies must rely on the scientific research forces of research institutions, such as universities.

Accordingly, such conditions determine that in technological innovation platforms in mega infrastructure construction, the support from experts and intellectual resources of multiple relevant fields should be guaranteed. Although these experts may not participate in the specific research activities of technological innovation on behalf of a certain organization, they can provide consultations and guidance with respect to the technological innovations based on their personal experiences and knowledge. In general, they are usually authority figures in a certain discipline with extensive experience.

2. The rotary/precession development of construction technological innovation

The rotary/precession concept (Ju 2005) crystallizes the formation of a technological innovation scheme as a process of constant comparison, gradual approximation, and final convergence. Some major problems in construction technological innovation management, such as technological innovation schemes, have a bearing on many objectives of mega infrastructure constructions, such as the quality, safety, processes, and risk prevention of the construction risk prevention. A scheme involves technologies, equipment, and people as well as the owners, construction units, and design units. Moreover, it extends to various other areas, such as the organization, culture, and economy, all of which require certain construction principles, management rules, and humanistic rules. Together, these features indicate that the system complexity must be managed from many different perspectives. Therefore, during the process of selecting an innovation scheme, many in-depth comparisons should be conducted on a broad and comprehensive scale. The conceptual models, effects of different schemes, and efficiencies of different equipment, personnel, and construction technologies should be thoroughly compared. The technological innovation of mega infrastructure constructions is an evolutionary process whereby the demand planning gradually approximates toward the actual construction requirements. During this process, all of the phases are closely linked and correlated with one another much such as concentric circles. This not only reveals the close integration between innovative activities and construction practices, but it also reveals the mutual rotary/precession-mode philosophy.

Generally, the technological innovation activities in mega infrastructure construction in practice are usually conducted through different independent and integral scientific research projects and are directly driven by the construction needs. The innovation achievements of the scientific research projects are then implemented during the construction practice, with feedback being generated that gives rise to new innovation requirements that, in turn, drive the implementation of a new round of scientific research projects. The construction consists of production needs, and the fact that construction needs drive the development of the entire scientific research project supports the construction need orientation of mega infrastructure construction technological innovations. Such innovations are mainly the product of applied studies; thus, the value of their final achievement is embodied in the actual constructions and practical applications.

Technological innovations in mega infrastructure construction integrate both scientific and systematic natures. The scientific nature is reflected in that it requires a respect for science, the principle of seeking truth from facts, the exploration and

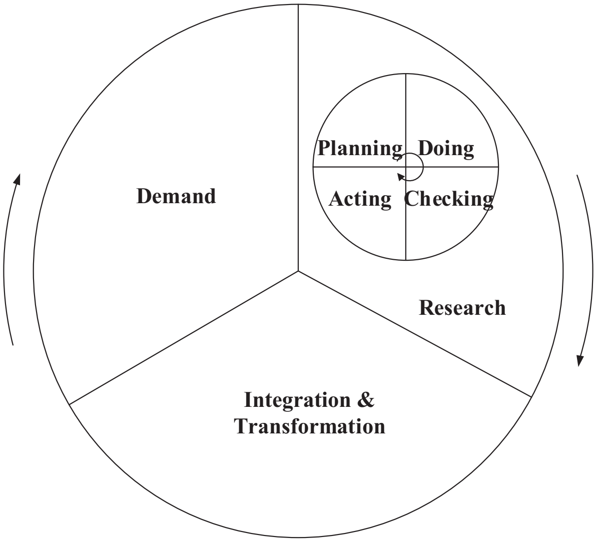

Fig. 7.12 Integrated management of the three phases of technological innovations in mega infrastructure construction

understanding of the objective laws of construction, and an accurate grasp of the technological path of implementing innovation projects. The systematic nature, on the one hand, is embodied in the correlation of multiple scientific research projects. For example, the scientific laws involved in these projects are usually strongly related. On the other hand, it is also embodied in the progressive relations between the different scientific research projects. That is, the end of one project is usually the start of another. Because of this feedback mechanism, different scientific research projects become correlated and successive, thus meeting the requirements that technological innovations should be scientific and systematic (see Fig. 7.12).

7.4.4 The Technology Management in the Full Life Cycle of a Mega Infrastructure Construction

From the project approval decision-making stage to the project implementation stage through to the final completion and delivery for operation stage, these processes constitute the full life cycle of a specific mega infrastructure construction. The whole life cycle of a project can be divided into four periods: the preliminary period, construction period, operation period, and retirement period. It can also be divided into the following six phases, (You 2009), namely, the planning phase (also called the preliminary decision-making phase), design phase, construction phase, completion acceptance phase, operation phase, and retirement phase, as presented in Fig. 7.12. Moreover, various aspects of technology management are involved in the full life cycle of a mega infrastructure construction (Li et al. 2005), as depicted in Fig. 7.13, such as technology selection, technology assessment, technology scheme design, technical control, and technology maintenance and management.

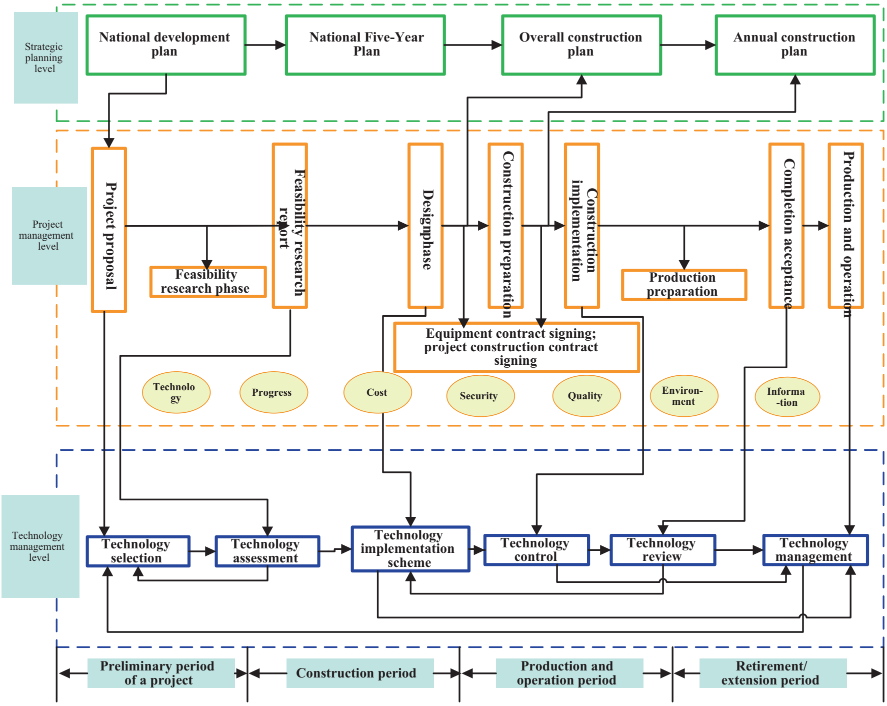

Fig. 7.13 Technology management activities throughout the full life cycle of a mega infrastructure construction

More specifically, in the project planning phase, the technology management activities include technology selection and technology assessment. Technology selection refers to the selection of technologies based on various factors, such as the types and functions of the various technologies and the requirements of the construction management project itself. The first step in the technological feasibility assessment is to evaluate the new to-be-constructed construction by comparing the technology systems of existing similar constructions with those of the proposed new construction in terms of processes and technical factors to identify the uniqueness of the new construction and the influences that such uniqueness and differences may have on the personnel, equipment, materials, and expenditure. Once such comparisons have been conducted, the overall technological feasibility of the proposed new construction is assessed. The managers of the construction project should adjust the decisions related to the technology selection based on the feedback of the technological feasibility assessment. During the project design phase, technology management selects the technology implementation scheme. In the completion acceptance phase of the project, an important task for the technology management team is the verification of the technology scheme. Technology verification during this phase refers primarily to the verification of the technology implementation scheme. With respect to the project operation phase, technology management includes the

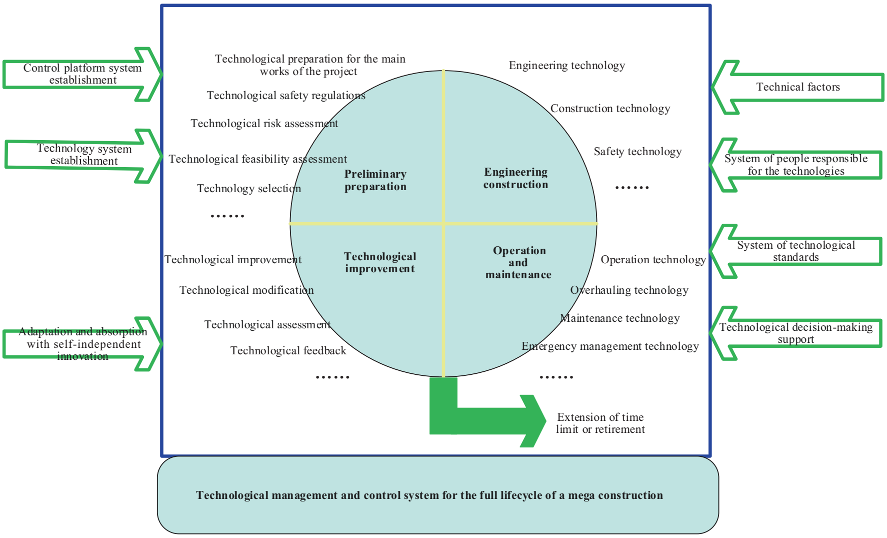

Fig. 7.14 Technology management models in the full life cycle of a mega infrastructure construction

comprehensive management of the operation technologies and the summary and analysis of the technology implementation scheme, the technical control system, and the technology verification results.

In addition, there are individually different though correlated management tasks for the technology management team in mega infrastructure construction throughout the four major periods of the full life cycle of a mega infrastructure construction, as presented in Fig. 7.14.

In the preliminary preparation phase, many processed works, such as the technology selection, technology feasibility analysis, technology risk assessment, technology security analysis as well as the technology preparation for the main part of the project, must be performed with a focus on the objectives of the construction project. Among these objectives, the technology security analysis in mega infrastructure construction involves treating a cluster of technologies as a system and determining the status of the technology security according to how well the system functions as well as the robustness and effectiveness of the system. Accordingly, the foundation of the technology evaluation system was based on selecting the appropriate technology, establishing adequate construction technology preparations, and conducting feasibility assessments, risk evaluations, and technology security function assessments.

The construction phase is a phase when the entire technology management system plays a critical role. The construction work of a mega infrastructure construction is a complicated process that calls for the coordinated collaboration of workers as they perform different tasks and the integration and synthetic application of multiple technologies. At the technology management level, there are two basic requirements, namely, to ensure that the construction process moves forward and adheres to the scientific rules and technological principles and to actualize the great potential of the technical teams working on the construction project as well as that of the technology equipment.

The operation phase of a construction involves construction overhauling and technology maintenance, as well as the incorporation of emergency management technologies. Together, these activities ensure that the technologies solidified in the hard system of a mega infrastructure construction will be stable and constant or that they can timely recover and maintain stability in the event of a fluctuation or mutation of technological functions and efficiencies.

After the completion acceptance phase of a construction, to put into practice the rationale that technology improvement should precede equipment failure for the long-term operation of a certain construction, it is necessary to make, well in advance, planning schemes and paths to build technology feedback systems. Specifically, in this period, another focus of construction technology management is the analysis and evaluation of all the construction technologies developed during the various construction practices. By summarizing the construction technology management achievements in the construction process, valuable technology management experience can be extracted and can provide guidance for future implementation in mega infrastructure constructions. Accordingly, while enriching the construction technology management theories, the management standards of the technology management teams will also be improved.

7.4.5 Establishing a Technology Management System for a Mega Infrastructure Construction

To accommodate the basic features of technology management in mega infrastructure construction, it is necessary to establish sound technical systems, reliable technical standards control systems, and responsible technology management systems. In the management process of the full life cycle of the construction. Highly efficient management is achieved by establishing correlations and interactions among different technology management factors, among various technical control indicators, and between information and knowledge.

In the technology management system of mega infrastructure construction, it is necessary to establish a management organization system that adheres to hierarchical authorization principles under certain authorization rules. In this system, the technological and management responsibilities, such as construction technology innovation, construction consultancy, professional development, capacity building, and technology standardization, can be allocated progressively. A technology management system for a mega infrastructure construction organization is composed of a technical factor system, a technical responsibility system, a technical control system, and a technical decision-making and support system. Among them, the technical responsibility system refers to the technology organizations and position authorization systems established within the business units, such as the design, procurement, construction, and debugging sectors; the technical control system refers to the technology organizations and authorization systems established within these business units and involve the functional departments such as the department of construction and the business center; the technical decision-making and support system refers to the establishment of technical decision-making and support organizations, which involves functional departments such as the business center, department of construction, chief engineering team, and construction science and technology committee.

The design of a technology management system for mega infrastructure construction project is comprised of certain features:

1. Establishment of the technical factor system

Technical factor systems are the technological units that correspond to the minimal task units of major relevant technologies with respect to construction design, equipment supply, construction work, and operation management. Such factor systems are characterized by features such as relative independence, integrity, and inseparability. Moreover, there is no intersection or connection between or among the various responsible personnel.

To build a technical factor system, the first step is to decompose the basic technology system and then establish a technical factor system to sort out the logical relationships among the different technological factors and finally build a technical factor system that is flexible with respect to the different projects, tasks, and organizations.

2. Establishment of a technical standards control system

A technical standards control system is a technology management system built to ensure that various segments of the construction process, such as the design, procurement, construction, and debugging, meet the overall technological specifications of the project, the requirements of legal norms, and the requirements of the technology management systems implemented under the request of safety inspection authorities and owners.

To establish the technical standards control system, the first step is to establish different control indicator systems for different technical factors and then build the mapping between the technical factors and the control standards. Simultaneously, the target value and the threshold of control under different safety, quality, and risk control levels should be established.

3. Establishment of the technical responsibility system

Technical responsibility refers to the responsibilities associated with completing a certain technical task. A technical responsibility system is a management system established to ensure that all of the technical activities of a construction project, including the construction work, technical research and development, and capacity building, can be smoothly conducted. Accordingly, this system manages different levels of positions that have clear divisions of labor and technical authorizations as well as collaborative relationships among these different positions.

A technical responsibility system must be built on the basis of a clear business-human-technology mapping, with a focus on role analysis, the analysis of the technical division of labor and authorization, and the analysis of relations among different technology systems.

4. Establishment of the technical decision-making and support system

A technical decision-making and support system is a system used to make hierarchical decisions concerning technical problems and to provide technical support for the technology responsibility system and the technical control system of the business center. Decision-making support is realized through the provision of information and knowledge about the technical control standards, tacit technical knowledge, technological potential risk, and relevant responsible persons by the respective persons arranged for different businesses.

By integrating the technical factor system, technical standards control system, technical responsibility system, and the technical decision-making and support system, an overall technology management system is accomplished. The mapping between the technology management system and other management layers in mega infrastructure construction is presented in Fig. 7.14. In this mapping, the roles and positions of the organizational management module are mapped to the corresponding technologies in the technical responsibility management module, indicating the ownership relationships among the various technical factors and their corresponding responsible persons. The mapping from the relevant technologies in the technical responsibility management module to the indicators and specifications in the technical control module indicates the standards and specifications that different technical factors should meet. These factors are designed to provide a basis for the technical decision-making that is required during the segment of the project. After a decision is reached, the information results will feed back to the responsible persons associated with technical factors in the previous three modules and drive them to make appropriate adjustments, thus further promoting the interactions and circulation of information throughout the whole process.

The technology management system is divided into five layers, namely, organization, process, business, control, and decision-making support, of which the core layer is the process layer. The technology management system is presented in Fig. 7.15. A technology management system is decomposed into independent sub-business units following the logical time sequences of the process activities in mega infrastructure construction. These sub-business units are then mapped to the necessary organizational personnel, necessary technical factors for the completion of certain business activities, and corresponding technical standards. The bottom layer refers to the processes of communication and interactions among the various knowledge supports for the technical decision-making. In the hierarchical model of basic management, the organizational management module is the only module that is dynamic in nature, and as such, this module unifies the management and scheduling of the process module, business module, technical control module, and technical

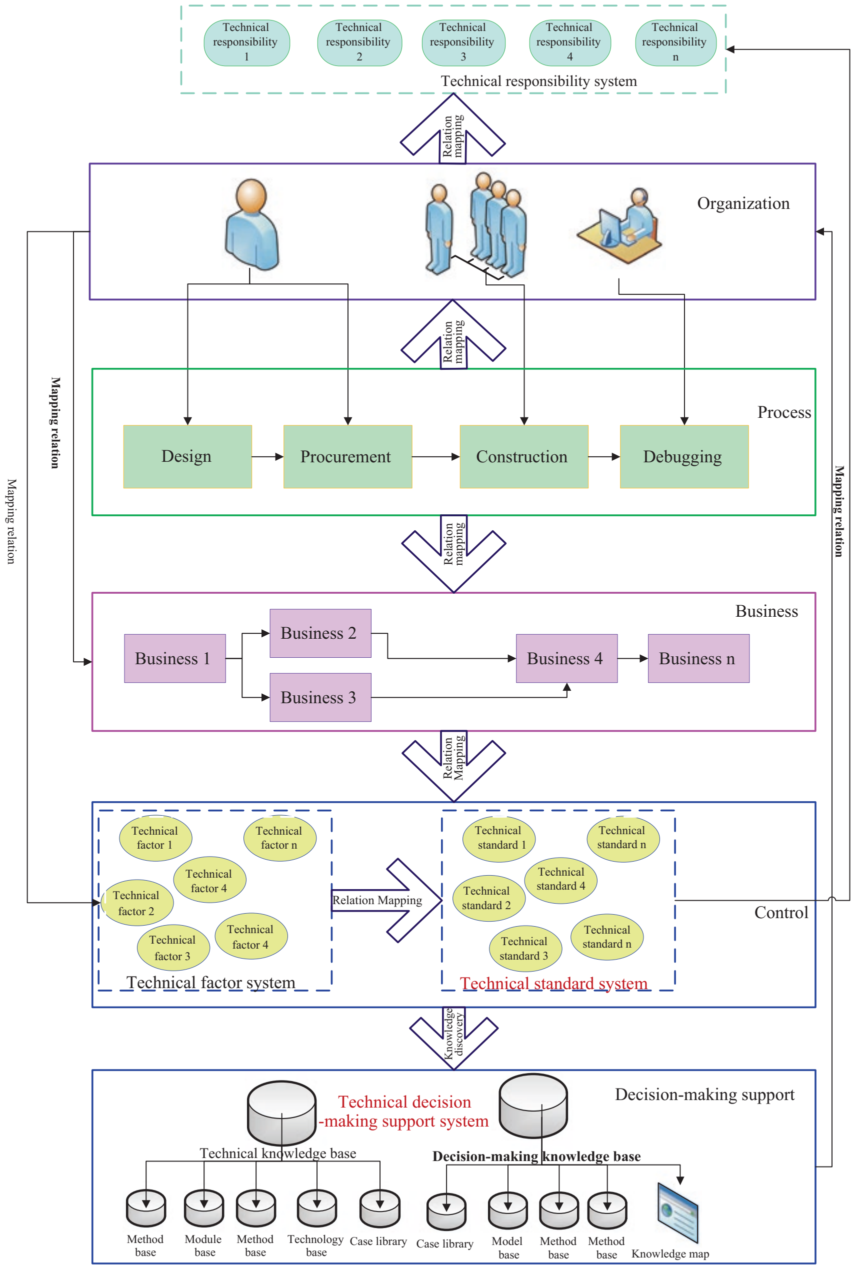

Fig. 7.15 The hierarchy model of the technology management systems in mega infrastructure construction

responsibility system module. On the one hand, the organizational management module assigns different technical responsibilities in the technology management module to different roles and positions in accordance with the specific processes of the design, procurement, construction, and debugging phases. On the other hand, the organizational management module connects the technical responsibility management module with the technical factor system to demonstrate the interrelationship between different technical factors and the corresponding responsible subjects. Because the indicators and rules and regulations in the technical control module establish standardized restrictions with respect to the technical factor system, the corresponding technologies and technical responsible persons in the technical responsibility system must simultaneously perform their own roles under the control of the technical standards system. Based on the mutual coordination mechanisms of the above modules, the technical decision-making support system (Sprague 1980) makes technical management decisions regarding the corresponding businesses. This system covers the technical knowledge base and the decision-making knowledge base and thus facilitates scientific decision-making for the specific businesses. After the decision-making process is complete, the decision results are reported to the organizational management module to further adjust and optimize the technical responsibility system and the technical factor system, to achieve the interaction and circulation of information flows throughout the entire technology management system.

7.4.6 The Implementation System of Technology Management in Mega Infrastructure Construction

The implementation and performance of technology management systems in mega infrastructure construction should not only be closely oriented toward the construction demand of mega infrastructure construction, but they should also focus on the social and natural environments of the constructions, design implementation, and performance systems for technology management. However, it should be emphasized that the focus of the implementation system design is not the arrangement of specific technology management tasks. Instead, the focus is on how to fully embody the meta-synthetic thought in the implementation process and integrate the technology management system and other tasks in construction management.

Here is an example. In the design phase, the foundation and environment, together with the crux of the project, the decision-making, the internal and external supervision, and the objective, are viewed as the core content of the system in construction. Among these, the foundation and environment encompass the construction safety culture and exerts influence throughout the whole construction process by facilitating the formation of the different management concepts, management and control system, quality assurance system, and performance management system. Together, these constitute the core of a management model that is composed of four key factors, namely, business, resource, manpower, and performance. Furthermore, after the classification, streamlining, and standardization of the different businesses, the resources, such as manpower, capitals, technologies, and information/knowledge, are loaded. These resources provide specific activities and tasks. For example, by having control of the working process and the technologies used during critical points and the corresponding performance evaluation of the control results, a management mode characteristic of vertical management, hierarchical authorization, process orientation, process control, internal and external restriction, standardization, routinization, informationalization, and target-oriented operations will be established, and the comprehensive and full-process management of mega infrastructure construction will be achieved while in pursuit of the overall management goal. In addition, technology management will be equipped with the capacity of constant improvement through process optimization. This process is the engine for the running of various technology management activities. Changes in the process require corresponding modifications of the procedures, standards, and specifications upon which the performance of the process relies.

The implementation and performance of technology management focus on five main parts: the foundation and environment, kernel, decision-making, internal and external supervision, and target in construction. The implementation and performance of technology management in mega infrastructure construction are illustrated in Fig. 7.16. With the cultural concept of green and ecological engineering as the foundation, managers must build the technology management and control system, quality assurance system, performance management system, and risk pre-warning system using the intelligent collaboration platform of the architecture that is composed of industrial norms and systems for both home and abroad. The creation and building of all these systems are performed as part of the technology management process throughout the full life cycle of mega infrastructure construction (Li 2012).

Consider the intelligent collaboration platform as a supportive technical platform for technology management. When data, technologies, and theories such as artificial intelligence in the construction process are implemented, the man-machine interactions become possible, and the intelligent level of the technology management systems is improved. In this platform, different segments work together to complete a specific task and share resources with one another. None of these segments could separate from the other segments and function independently, as they rely on one another and condition one another, and thus can only function under a reasonable division of work and coordinated operations. Consequently, the kernel of the implementation and performance system is formed by four major factors, namely, business, resources, manpower, and performance factors. Under the strategy of hierarchical business management, there are three top-down levels, namely, the strategic, process, and task levels. By allocating resources such as manpower, technologies, information/knowledge, capital, and equipment to specific tasks and controlling the key nodes combined the evaluating of corresponding business performance; a unique technology management mode is formed. This management

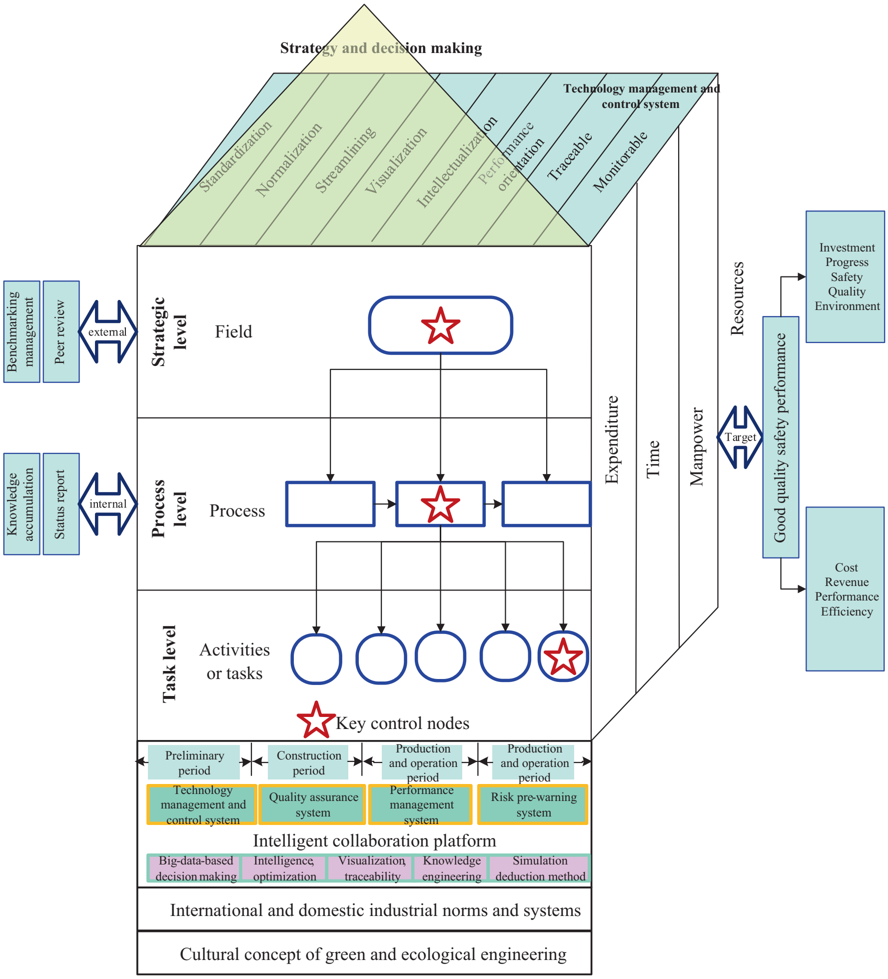

Fig. 7.16 The implementation and performance of technology management in mega infrastructure construction

mode is restricted by internal and external conditions, such as expert evaluation and knowledge accumulation, and as a result, it achieves the good quality safety performances that are the goals of such management modes. Through methods such as hierarchical authorization, vertical management, process orientation, process control, internal and external restrictions, standardization, routinization, informationalization, and target-oriented operations, such management modes can function and facilitate standardization, normalization, streamlining, visualization, and intellectualization. Thus, because this model relies on the technical improvement and the process optimization links and because it enjoys the strength of sustainable development, it has the capacity of constant improvement and loop optimization.

7.5 Comprehensive Control and Coordinated Management at the Mega Infrastructure Construction Site

The mega infrastructure construction site refers to the location of the main project. It is also the final place where the construction entity materializes as a concrete object.

Whether it is a general construction or mega infrastructure construction, because site management activities of the two share a large number of similar tasks, the two exhibit many similar management behaviors, processes, and technologies. Therefore, this is not a study mega of the infrastructure construction site because it portrays no significant differences from the general construction site. Rather, the primary focus is on-site management and the activities and problems that fully reflect the managing complexity of mega infrastructure construction. Even so, due to the productivity of mega infrastructure construction management activities, only three site problems, all of which possess typical characteristics of mega infrastructure construction, are examined. The intent is to reveal that with respect to mega infrastructure construction site management, there exists a wide variety of complexity-based scientific problems that are worthy of attention.

7.5.1 Overview of the Complexity of the Mega Infrastructure Construction Site

1. The site space is a multi-scaled space.

For many years, people have surmised that a construction site is the site of a construction entity. However, regarding mega infrastructure construction, the space scale of the site is much larger (Jog et al. 2011). First, the construction itself is likely to be a large-scale entity. For example, the Qinghai-Tibet Railway of China is 1956 km long; the eastern route of the South-to-North Water Diversion Project involves nine provinces and municipalities of China and covers a wide area. Second, with the conversion of the site construction method of mega infrastructure construction from site fabrication to site assembly, increasingly more construction entity components are manufactured by factories. Such components are large in number and demanding in quality, and thus, they are often produced jointly and simultaneously by many suppliers in different locations (Long et al. 2014). Functionally, the locations of these suppliers should also be considered construction sites or the first sites of construction, whereas the construction site of the construction entity is simply the assembly place of the products created in the first sites. As previously discussed, the construction of the Hong Kong-Zhuhai-Macao Bridge used over 400 thousand tons of steel box girders. Its plate units were manufactured by four factories that are several thousand kilometers away from one another. The assembly of steel box girders was completed by an assembly plant in Guangdong Province, and the girders were then transported by sea to the bridge construction site. For such a complex construction supply chain, the construction site cannot be merely understood in a narrow sense as the site of the construction of some object. Instead, only by considering a supply chain with large-scale space as a complete construction site can an exact and overall understanding of the actual connotations of a mega infrastructure construction site be formed (Young 2011).

2. The site environment is not entirely known.

In general, the environment of the mega infrastructure construction site is much harsher than that of a general construction site in that there always exist high mountains and deep waters, strong wind and rough waves, as well as heterogeneity and homogeneity in the natural environment. Although much research and exploration have been conducted during the early stages of construction, due to the large-scale and unknown environment of construction site, it is still difficult to know, comprehensively, deeply, and accurately, the details and rules of the construction site environment. Moreover, because man's ability to understand the complex rules of natural phenomena is relatively limited, certain complex rules cannot be entirely known even over a long period. Therefore, the creating of activities of a construction site begins even though the construction environment and specific respective laws are not fully understood. Thus, on the whole, the management subject of the mega infrastructure construction site always promotes the construction and management of mega infrastructure construction when the uncertain environment is not entirely known or is even substantially unknown.

3. The thinking and ability of the site subject are limited (Xu and Li 2012; Li et al. 2016; Sandin et al. 2014).

Furthermore, in today's world of an ever-increasing scale of mega infrastructure construction, its complexity is similarly increasing. However, the site management experience and ability of the construction management subject are usually accumulated based on relatively small-scale and low complexity constructions. Therefore, when faced with new problems in mega infrastructure construction site management, the management subject tends to be relatively unprepared to manage them. Such behavior indicates that a relative lack of the subject's ability to manage site complexity is a common phenomenon in mega infrastructure construction site management. In contrast, the general construction subject occupies a commanding position and manages the problems on site based on their wealth of experiences.

In addition, people's tendency when solving problems is to treat complex problems through a simple thinking mode, to analyze multifactor problems through a single-factor or few-factor thinking mode, and to analyze instinct, indirect, and long-association-path problems by manifesting direct and short association path problems. Through such thinking modes, it is difficult to form a smooth and transparent thinking path to analyze site complexity and even more difficult to completely and clearly resolve complex problems at the mega infrastructure construction site.

It should be particularly noted that the mega infrastructure construction site focus is on changing virtual construction in the mega infrastructure construction design into entitative construction. The construction design, however, proposes a successful construction creation path via a blueprint. Along this path, there are numerous unsuccessful hidden paths. These unsuccessful paths are uncertain and unknown to the site subject, and even the designers cannot predict whether the path in front will be successful or unsuccessful. Therefore, the complexity and risk at the construction site are greatly increased.

It is required that the subject be comprehensively innovative in the areas of management philosophy, organization patterns, technology, and management to handle the complexities that emerge at the construction site. This includes not only the innovation demand required of practical problems in mega infrastructure construction, that is, the unavoidable innovations in construction, but also the innovation redundancy formed by the subject's excessive innovation preference, such as the pursuit of the requisite first-time activities and breakthroughs in mega infrastructure construction through innovation. Such innovative thinking and behavior by the subject will add many unnecessary risks and difficulties to the mega infrastructure construction site and result in the creation of many problems in complexity management.

When analyzing from multifactor horizontal associations, connections between multitasking interfaces, to the coordination among the site apparatus, materials, and personnel, a series of new and complex management problems in mega infrastructure construction site is discovered (Lavikka 2015). Some prominent and typical significant problems thereof include the unique scientific problems in mega infrastructure construction site management. Accordingly, three typical scientific problems appear to be the most common.

7.5.2 On-Site Comprehensive Quality Control

With respect to the connotations and features of quality in mega infrastructure construction, it is important to first know and understand them from the physical functions of the hard system and their overall objective with respect to the greater picture of mega infrastructure construction.

First, according to the long life cycle of mega infrastructure construction, construction quality refers to the overall durability of the construction in a macro sense. Durability is a common concept used to describe quality in the field of construction and materials. In this context, durability is the ability of materials, apparatuses, and products to resist the impacts of the external environment and maintain its functions when in use. In general, the durability of an object can be decomposed into the abilities of its different dimensions. For example, the durability of concrete can be decomposed into anti-permeability, frost resistance, and erosion resistance. People's expectations of construction quality are reflected in the durability of the physical functions within the life cycle of the construction. *Thus, overall, the sign of quality is the durability of its overall functions in mega infrastructure construction.*

Therefore, site quality should be considered through a comprehensive analysis of mega infrastructure construction in the context of the overall system of all the factors relevant to quality, such as the quality of the construction materials, the level of the site construction equipment, the standards of the design, techniques and technologies, etc. On this question, two points must be mentioned.

1. Although the durability of a construction is primarily formed during the creating process on the site of a mega infrastructure construction, many activities, from construction planning and certification to construction design, technical standards development, and choices of suppliers and contractors, have significant impact on the durability of construction quality. Therefore, it is necessary to reflect on the formation of the durability through the systematic thinking of the whole process and the full coverage of the mega infrastructure construction entity rather than limiting the focus to on-site quality management activities.
2. Although the activities and elements of durability can be decomposed in a multidimensional way with respect to mega infrastructure construction in terms of association and causality, this does not mean that the overall level of the construction's durability is a simple superpositioning of the durability of the dimensions of these decomposed activities or elements, because construction durability is a matter of whole behavior emergence at a higher level than that of certain individual activities or elements. Although durability is concerned with site quality activities and elements, it is the result of the evolution of these activities and elements combined with the complex formation mechanism.

Second, according to the large-scale assembled manufacturing common of on-site mega infrastructure construction, *construction quality at a micro level is represented by the stability of the materials and components.* The creation site is in demand of a large quantity of materials and components in mega infrastructure construction that are the basic elements of a hard system and whose quality relates directly to the overall quality of the construction's hard system in mega infrastructure construction. With respect to this problem, three points are noted.

1. The relation between the quality standards of basic materials and components and the construction's life cycle is always nonlinear in mega infrastructure construction, that is, the quality standards increase more than the scale and life cycle of the construction. Only when this relationship is adequately assured can the overall construction quality be guaranteed.
2. Under strict quality standards, only by keeping the quality of materials and components of the construction stable (consistent) can the micro quality of the site be ensured. The concept of quality stability (consistency) refers to the quality index of each lot of materials or each component. This index should remain within the permissible range of the established quality standards. The materials and components, which are numerous in quantity, are the basic elements of the construction hard system in mega infrastructure construction. Therefore, with respect to overall construction quality, what should be considered is not that some individual or parts of certain materials and components are quality products but that the quality of all of the materials and components generally and consistently meets the established standards, namely, the quality exhibits stability and consistency at a micro level, thus guaranteeing the overall durability of the mega infrastructure construction.

3. Based on industrialized production, in today's world, the proportion of assembly on the site is increasing in mega infrastructure construction. However, as hard systems cannot be produced completely through site industrialization, such systems still require manual labor in mega infrastructure construction. In this way, the actual quality of a hard system depends on both the quality of the industrialized production and that of the manual on-site assembly in mega infrastructure construction. Such a mixed mode of site construction leads to a complex formation mechanism of construction quality such that the quality of an artificial site construction is more likely to exhibit recessive fluctuations and variations because of people's psychological and physical states. However, such situations are not only difficult to observe and discover but difficult to predict and control as well.

Therefore, whether it is quality durability at a macro level or quality stability and consistency at a micro level, they are both core connotations of site quality in the construction site quality management of mega infrastructure construction. As such, it fully embodies the complex cognitive principle of management theories in mega infrastructure construction. According to this principle, quality management activities at the site are based on the quality stability of materials and components at the micro level of construction. However, these activities cannot simply and completely be decided by the micro quality in mega infrastructure construction because the quality properties of the site materials and components undergo a series of changes during the construction process, such as fluctuations and variations as well as the recessive transmission of the properties brought about by these changes. As the durability of the construction is the result of the emergence of the overall construction quality behaviors in mega infrastructure construction, it cannot be perceived as the simple superpositioning of the micro quality properties of the materials and components.

Based on the above, to fully comprehend the quality management of a mega infrastructure construction site, several factors should be considered.

1. The complex association and emergence mechanism of macro quality durability and micro quality stability in mega infrastructure construction involve numerous factors, such as the study of fluctuations and variations in the construction site quality formation process, the transmission path and rules of quality fluctuation, the formation causes and thresholds of quality variations, hazard analyses and preventive measures of quality variations, among others.
2. The relative influence of the recessive quality flaws in a former stage on the quality in a later stage and its mechanism in mega infrastructure construction are important factors to consider. For example, a study of the objective rules of site quality stability formation and quality variation begins with the variability of quality and focuses on the interactions between the two types of rules.
3. The dynamic control technology of the site quality is based on stability. Since one of the goals of site quality is the quality stability at the micro level in mega infrastructure construction, the focus of quality control should be converted from static local stability to the prevention of systematic quality fluctuations and variations.

For example, in the industrialized production process of large quantities of construction components, a real-time analysis of the causes and impacts of the systematic quality fluctuations and the preventions of such quality fluctuations produced in every procedure from spreading and expanding along the manufacturing path should be conducted, and the quality flaws and incidents should be totaled. Therefore, based on the real-time and continuous data collection of manufacturing quality, a data analysis should be conducted, and a study of the quality formation mechanism should be performed, and a logical inference regarding the problem of quality stability should be established. Furthermore, a plan must be developed to prevent the formation paths of systematic quality fluctuations and variations and to comprehensively apply all of the aforementioned technologies and methods to reveal the quality stability rules of a mega infrastructure construction site.

4. Accordingly, based on the qualitative and quantitative methods and the computer technology, the influence of construction site scenarios and conditions on construction quality stability should be simulated, and analyses of the formation of the rules of construction quality fluctuation paths, causes and thresholds of quality variations, damage from quality variations, as well as the various control technologies and preventive measures of quality stability must be performed.
5. On the construction site, according to the construction thinking principle, one-to-one-scale trial manufacturing or tests, i.e., full-scale testing that provides empirical data to find a technology instructor and optimize construction plans, should be conducted prior to determining and obtaining relevant site construction technologies and parameters. Moreover, the practice of first construction approval should be conducted on every lot of products of the same type, as it has been demonstrated that this system of first construction approval can sufficiently summarize the construction technologies, methods, and specific quality control measures that play an exemplary role in improving construction quality and guaranteeing zero defects. In addition, technical measurement centers and labs should be established to ensure that all construction quality management activities are based on scientific, reliable, and credible data.
6. Site quality activities are organized systems of construction and are, in terms of time, the continuation of the prior designed activities in mega infrastructure construction. Thus, construction design should be considered when developing a quality management philosophy of design and construction integration. Subjectively, site quality activities are not only the tasks of construction units but also the cooperative tasks of many units including owners, designers, contractors, suppliers, supervisors, etc. (Doloi 2011). Therefore, these subjects constitute an effective quality control organization and establish a corresponding quality management system, as presented in Fig. 7.17.

Site management in mega infrastructure construction includes not only quality management but also the management of cost, safety, progress, and environmental protection (Golparvar-Fard et al. 2011). In other words, site management in mega infrastructure construction is quality-centered multiobjective coordinated management. However, in mega infrastructure construction, quality and progress tend to

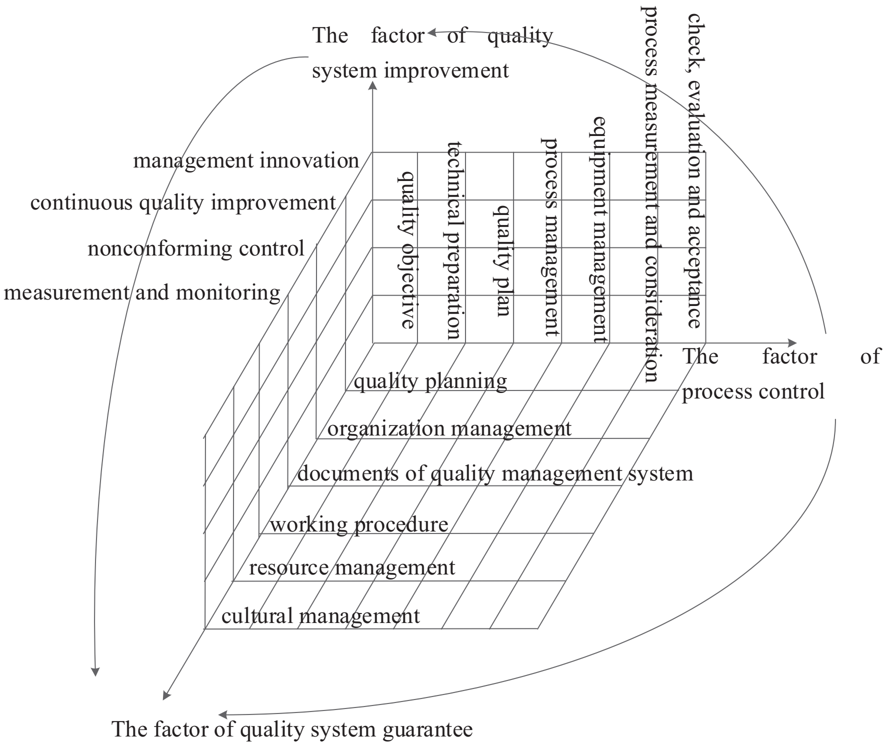

Fig. 7.17 The three-dimensional site quality management system

contradict each other. For example, progresses only with quality and quality only with progresses are undesirable traits at a construction site, because with poor quality, fast progress is worthless, and similarly, slow progress does not necessarily equate to good quality. In construction, although the motto is "quality first," it does not always determine the real ranking for the multiple objectives of site management. Thus, in this context, quality first is understood to balance and optimize other objectives on the premise of guaranteeing quality, thus leading to common consensus of site management in general construction. However, with respect to mega infrastructure construction, due to the long life cycle of construction and the complexity of the overall quality, it is particularly important, albeit difficult, to pursue a quality first practice (Tchidi et al. 2012).

In addition, safety management is always a significant management problem at a construction site. It is obvious that with respect to the mega infrastructure construction site, management will face numerous difficulties and challenges. Thus, it is essential that the management of conventional site safety issues be studied and improved, that new site safety problems caused by the complexity of the site be intensively analyzed, and that the rules to form new safety management technologies and methods in mega infrastructure construction be explored and revised.

Because such safety problems caused by site complexity are often the result of a strong lateral correlation of the site elements, the transmission mechanism is more recessive and uncertain and thus much more likely to transform local breakdowns and small incidents into large-scale or even global disasters. Therefore, it is inappropriate to treat them as general low-level, small-scale safety incidents. Rather, they should be considered as potential safety disasters with global risks at the mega infrastructure construction site. Therefore, this type of safety management specific to the mega infrastructure construction site and an analysis of the complexity risks with respect to mega infrastructure construction are discussed in Sect. 7.6.

7.5.3 Coordinative Management of On-Site Technologies and Supply Chains

As previously discussed, comprehensive quality control at the mega infrastructure construction site is both important and complex. Thus, it is evident that the most significant factor regarding site management is the coordinated management of site technologies and supply chains under the principle of guaranteeing quality stability, as these two aspects are the most closely related to the formation of site construction quality in mega infrastructure construction.

7.5.3.1 Coordinated Management of On-Site Technologies

Technology management based on quality stability refers to the selection and innovation of key technologies grounded on guaranteed construction quality (Mlecnik 2013). From a direct perspective, it seems to be only technological. However, the selection and innovation of technologies require a conducive environment and a mechanism for integrating related resources, which means that the selection and innovation of site technologies must be supported by corresponding management and must be accomplished by a comprehensive technology management system. To achieve it or to do it well, the subject must have a profound understanding of construction site technology management, and based on this understanding, he must establish an effective comprehensive system that involves the coordinated and collaborative management of the multiple subjects within the system.

In general, the selection and innovation of key technologies on site are a breakthrough in the technological development process of mega infrastructure construction. It not only involves a direct technology providing subject and technological innovation subject, but it also correlates closely with the technological economic analysis, technology risk evaluation, and technology quality evaluation conducted by technological decision-making subject and on-site management subjects. Accordingly, the on-site selection and innovation of key technologies are a comprehensive and multi-subject coordinated management activity in mega infrastructure construction. It requires us to have an understanding that exceeds the construction level and comprehensively combines construction benefits, economic benefits, and social benefits of the technological selection and innovation with the long-term strategies and social responsibilities of the construction.

More specifically, the core task of the coordinated management of site technologies is, through systematic analysis and design, to combine the management of the objective, organization, system, mechanism, etc. in the technological selection and innovation process to create a complete, effective, and operable management system, rather than to perform only the pure job of technology research and development in mega infrastructure construction. In this system, not only can the leading role of the core subject, the dominant role of the enterprise, and the supporting roles of the other units be fully actualized, but the explicit mechanism, process, and procedure can also work effectively, meaning the whole process of technological selection and on-site innovation can satisfy the site construction quality standards.

7.5.3.2 On-Site Coordinated Management of the Supply Chain

Another important site management activity that guarantees quality stability is the management of the chains that supply bulk essential goods, such as materials, equipment, components, etc., in mega infrastructure construction. This includes the physical quality of materials and the performance quality of the equipment at the micro level, that is, the quality stability of bulk materials and components. Accordingly, the site generally adopts the industrialized automation of components and intelligent manufacturing technology in mega infrastructure construction. Practice proves that automatic and intelligent manufacturing technologies not only effectively guarantee the high standard and stability of construction site materials and components and the construction progress requirements, but they also strongly promote the innovation mode of goods supply chains in mega infrastructure construction site.

Such supply chains exhibit a series of new features and objectives:

1. To develop a site that incorporates a form of large-scale distribution in mega infrastructure construction
2. To develop a construction and industrialized manufacturing construction site that has a strongly correlation with real time
3. To develop supply chains that form a complex hierarchical net that regards multiple homogeneous and heterogeneous suppliers and producers as nodes (Ma and Gong 2009)

Accordingly, on-site supply chain management requires profound and comprehensive coordinated management philosophies and new abilities to manage the complexities in mega infrastructure construction. A typical case of on-site management in mega infrastructure construction illustrates this concept.

The superstructure of the Hong Kong-Zhuhai-Macao Bridge in China is a steel structure, and as such, steel is the main component of the bridge. The 425 thousand tons of steel used in this bridge is equivalent to the amount of steel used in the AngChuan Zhou Bridge in Hong Kong.

Because its quality standards had to reach or exceed those of the AngChuan Zhou Bridge in Hong Kong and the San Francisco-Oakland Bay Bridge, the Hong Kong-Zhuhai-Macao Bridge was designed to have a service life of 120 years, which is consistent with British standards. While its orthotropic steel bridge deck is its key to anti-fatigue, the U-shaped rib angle welding seam of the bridge's steel plate is its key to quality. That said, it is difficult to control quality and even more difficult to guarantee the quality stability of a mass construction.

It is evident, given the status quo of steel bridge structure manufacturing at home today, that the key processes of making a girder plate unit, such as blanking, assembling, and welding, depend primarily on manual or semi-mechanized work. Despite the implementation of industrialized production, the automation level is low, and the quality of steel structures, restricted by the welder's techniques and mechanical equipment, is low in quality stability and production efficiency. However, the high cost, extended construction period, and human crowd strategy in girder manufacturing abroad do not fit the reality of the Hong Kong-Zhuhai-Macao Bridge project. Therefore, the only option is technological and management innovation. Only by integrating technological and management innovation into a complete on-site technology management coordinated system can the challenges in the manufacturing of girders for the Hong Kong-Zhuhai-Macao Bridge be managed.

To be specific, first, the key to the mass manufacturing of plate units lies in the stability of the quality. However, because the automation level of the traditional techniques is low, the workers' direct participation is substantial. In this way, even if the worker is highly skilled, the fluctuations in such factors as his physiology, psychology, mood, and site environment can result in quality instability with respect to the products. Therefore, to stabilize the quality of the mass plate units, the degree of participation of the people involved in the manufacturing process must be minimized to vigorously increase the automation and robot level in the manufacturing process. With respect to small-size plate units, stability can be realized by simply utilizing an automatic continuous manufacturing mode, which is one of the management strategies for coping with the challenges in the manufacturing of girders for the Hong Kong-Zhuhai-Macao Bridge.

Second, despite the large volume of the overall assembly unit of the steel box girders, the small segment assembly and welding of the box girders can be completed directly according to the linear synchronous techniques of bridge manufacturing and can effectively guarantee geometric accuracy while also greatly shortening the assembly cycle. With regard to the large segment assembly, providing a relatively closed, stable, and standardized environment is constructed; that is, as long as the assembly is completed inside the plant, then factors, such as the weather, that negatively influence assembly progress and quality can be prevented. Furthermore, the standardized assembly of the plant is beneficial to realizing the goal of zero harm, zero pollution, and zero incidents. In addition, with respect to the problem that high-level assembly workers are urgently needed to build steel girders, as the automated manufacturing mode of plate units greatly economizes top-line, high-level human resources, it can effectively transmit and transfer as many high-level personnel as possible to the assemblage of steel girders, thus relieving the challenges associated with achieving steel girder assembly quality and progress and realizing the balance of human resource allocation in the manufacturing of steel girders. This is another management strategy for coping the challenges of the manufacturing of girders for the Hong Kong-Zhuhai-Macao Bridge.

Thus, the management philosophy for managing these challenges and difficulties is to realize the least personnel for plate unit manufacturing and the best personnel for overall assembly through the transformation from industrialization to automation and intelligentization, that is, to realize systematic resource optimization allocation and improve the ability to manage complex management problems in the manufacturing of steel girders through a coordinated comprehensive technology management system.

To sum up, to cope with the challenges in girder manufacturing at the construction site of the Hong Kong-Zhuhai-Macao Bridge, a management system that is aligned with technological management and that combines the two into an integrated coordinated managing system is established. The top design for such a system is composed of several principles:

1. The subject group of the system is composed of the owner as well as many suppliers and producers. In this subject group, the owner, i.e., the girder manufacturer of the Hong Kong-Zhuhai-Macao Bridge Authority plays a leading and dominant role and, as such, becomes the core subject of the subject group. In this sense, the whole supply chain presents a distributed network structure (Bosch-Sijtsema and Henriksson 2014; Mok et al. 2015).
2. The suppliers, as the subjects of technological innovation in the supply chain, implement the overall technological and management innovations of the enterprise according to the actual situation of the enterprise itself.
3. In a market economy, the technological selection and on-site innovation are realized through fair and reasonable market contracts in mega infrastructure construction.

These top design principles fairly reflect the standard relationship between owners (government agents) and suppliers and producers (enterprises) based on the dual effect of the government market in mega infrastructure construction.

In the practice of supply chain coordinated management, the target orientation of the manufacture of girders for the Hong Kong-Zhuhai-Macao Bridge endows the owners in the supply chain with many new responsibilities.

First, the owners should implement strategic reorganization and rearrange the relevant technological selection and innovation activities, such as the selection and optimization of the technological innovation subject, the establishment of the technological innovation platform, the design of the technological innovation system, the cultivation of the technological innovation subject, and the supervision of the whole technological innovation process, which fully embodies the new comprehensive functions of technological management and supply chain management in mega infrastructure construction. Second, according to the prediction of the required quantity of steel girders for the Hong Kong-Zhuhai-Macao Bridge and the production capability of the relevant enterprises, enterprises of steel girders form a distributive and strong-coupling manufacturing network. To facilitate the owners in analyzing, handling, coordinating, and executing abilities aligned with the network, the coordinated management of the multi-subjects in the whole supply chain through to organization innovation should be guaranteed to reflect the adaptive selection principle of the owner in coordinated management through system supplements and clear management authority interfaces.

In addition, the supply chain in mega infrastructure construction, in essence, is a market behavior that requires the owner to respect the market status of the supply enterprises, respect the contracts and regulations signed by all parties, and respect the basic rules of the market economy. It is required especially that the owners fully reflect the spirit of these concepts through relevant contracts.

The owner's implementation of these principles arouses the enthusiasm and technological innovative spirit of the enterprise through the market lever. In the meantime, the contracts, as the agreement of the market relationship, guarantee resource allocation optimization within the track of the market mechanism, ensuring that the rights and interests of all parties as well as the behaviors of the owners and suppliers represent the continuity and constraints of the entire process in a legal context. Accordingly, it fully guarantees the coordinated effect among the multi-subjects in the supply chain.

In practice, coordinated management as described herein has ideal effects. Despite the large manufacturing quantity and the strict quality standards of steel girders for the Hong Kong-Zhuhai-Macao Bridge, the coordinated management of the supply chain forms a brand new mode of site production and supply chains, which, compared with traditional manufacturing techniques, improves production efficiency by 30%, thus stabilizing the welding quality and reaching a flaw detection FTY of over 99.9%. For the first time at home, the workshop operation of large-scale steel box girders, transferred from the traditional extensive management of the construction site to an automatic and refined management mode, is realized.

Currently, the overall technological innovation level of the manufacturing of the steel box girder structure for the Hong Kong-Zhuhai-Macao Bridge in China is the highest in the world.

7.5.4 On-Site Comprehensive Disaster Reduction

Since ancient times, general construction, especially the creation activities, has included the clear function of disaster prevention and reduction in mega infrastructure construction. For instance, the building of houses by ancient civilizations was one of the earliest construction creation activities. Its direct purpose was to keep out wind, rain, and inclement weather and protect the people from attacks by wild animals and from other natural disasters. The beginning of the history of the Chinese civilization generally begins with the story of King Yu combating the flood. It is said that in ancient times, the Yellow River flooded and the sage King Yu led the people to dredge water channels and broaden narrows, which was a significant hydraulic project at that time. After 13 years, the project eventually brought benefits and abolished the harm, successfully preventing floods by controlling water. This was the beginning of the Chinese agricultural civilization.

Today, many proposals for mega infrastructure construction demonstrate that they have clear goals and functions geared toward disaster prevention and reduction, such as flood control and ecological improvement.

The construction of mega infrastructure construction and its function, which is realized after its construction, are closely related with the environment. In particular, the various natural disasters that may appear within the overall lifetime of the construction have the greatest impact on mega infrastructure construction. These large-scale natural disasters, such as earthquakes, tsunamis, and volcanoes, often result in extensive damage to the construction and further cause tremendous harm to human life and property. Even if the actual occurrence of the natural disasters is extremely short, the destructive effects caused by them are likely permanent. For example, an earthquake leads to the collapse of dams, which triggers a large-scale flood, or a tsunami damages a nuclear power station, causing a permanent nuclear radiation disaster that may last for centuries. Therefore, an important task of site management in mega infrastructure construction is to strengthen the prevention of and reduce the damage caused by large-scale natural disasters while simultaneously engaging in construction creation.

Although the starting point of mega infrastructure construction is to benefit human beings, during the process of planning and creating a man-made construction entity, the original natural environment and ecological balance may need to be changed or even destroyed, which may interrupt the natural laws and even contribute to a natural disaster. Consider the construction of a large reservoir as an example. Whereas water storage and control should be positive and beneficial, the construction of the project simultaneously reduces the downstream water volume and lowers the water level, possibly causing the downstream river bank to collapse and the lakes to become swamps. In this sense, a disaster is caused by the negative effects of the function profile on the construction.

The construction at a mega infrastructure construction site should also avoid such disasters as construction damage that is directly caused by human behaviors and low construction quality. The so-called jerry built project, in fact, refers to man-made disasters caused by man's behaviors and actions at construction sites. Moreover, long, large bridge tower piers are intended to prevent ship collisions and tunnels should prevent fires, reflecting man's prevention of potential disasters (man-made disasters) on the site of mega infrastructure construction.

It is evident that both mega infrastructure construction and the mega infrastructure construction-environment compound system may lead to disasters and that disasters may be caused by natural laws, by human behaviors, or by a combination of the two factors. Therefore, although the original objective and function of mega infrastructure construction are to prevent and reduce disasters and the damaged they cause, in reality, new disasters may occur during the construction process. Thus, construction management at the mega infrastructure construction site should focus on preventing and reducing disasters that are especially pertinent to the construction itself (Tsai et al. 2014).

Mega infrastructure construction management should take a positive, yet cautious, attitude toward various potential disasters. First, do not give up eating for fear of choking. In other words, do not stop the construction due to the potential disasters that may arise during the construction and operation period. At the same time, throughout the lifetime of the project, beginning with the construction planning, and, especially during the on-site construction period, all involved subjects and parties should improve their knowledge and respect of natural laws, reinforce the principle of solving problems according to objective laws, enhance the science of site construction, strengthen the standards, and constrain subjects' behaviors to guarantee the realization of the goal of disaster prevention and reduction (Chen et al. 2013).

In particular, because the features of mega infrastructure construction include large-scale, complicated technology and multi-scale, diverse disasters, the work of on-site disaster prevention and reduction appears to be more complicated and challenging.

Although the entire construction process bears the responsibility for disaster prevention and reduction in mega infrastructure construction, it is understood to be a scientific problem for site management of mega infrastructure construction.

This is primarily because the site activities of mega infrastructure construction are the core activities of the construction creation. The completion of the construction entity is an on-site activity, and such construction activities as planning, designing, and constructing supply chains are all early-stage preparations and supports for construction site activities. Especially, the core features of mega infrastructure construction, such as construction quality and function stability, are created on site, and the construction's systematic task of disaster prevention and reduction is also performed and reflects its significance on site. Therefore, an analysis and study of disaster prevention and reduction in mega infrastructure construction based on site management activities in mega infrastructure construction can best reflect the practicality and timeliness of the construction's disaster prevention and reduction strategy.

In addition, whether it is about natural disasters or man-made disasters, disasters are regarded, in practice, as a type of scenario or phenomenon, and thus how to prevent these disasters and reduce their serious consequences in mega infrastructure construction management are the focuses herein. Accordingly, this requires incorporating this task into the practice of construction site management and confronting inevitable real scenarios and phenomena to study disaster prevention and reduction in mega infrastructure construction. Doing so will better reflect the site subject's construction thinking and behaviors regarding disaster prevention and reduction on the construction creation site and reflect the practical significance of studying this issue.

7.5.4.1 Overview of Disasters in Mega Infrastructure Construction

1. Connotations and categories of disasters in mega infrastructure construction

In a general sense, a disaster is "a sudden, calamitous event that causes serious disruption of the functioning of a community or a society causing widespread human, material, economic and/or environmental losses which exceed the ability of the affected community or society to cope using its own level of resources" (UN/ISDR 2007). This definition emphasizes two fundamental features of disasters. First, disasters may be caused by a natural disaster or human behaviors. Second, disasters have harmful consequences, the seriousness of which is determined by whether the consequences exceed the bearing ability of the area.

The disasters closely related to mega infrastructure construction are natural ones, such as geological disasters, e.g., earthquakes, river deposit, and river swampiness, geomorphological disasters, e.g., landslides and soil erosion, meteorological disasters, e.g., wind damage, drought, and rainstorm, and hydrological disasters, e.g., floods and tsunamis. The other type of disaster is the man-made disaster, such as construction economic disasters, e.g., construction collapse and inundation of hazardous substances, social life disasters, e.g., fires, wars, and terrorist attacks, and ecological disasters, e.g., environmental pollution and uncontrolled population growth. Natural disasters are primarily large-scale phenomena in the mega infrastructure construction-environment system, whereas man-made disasters are large-scale phenomena that occur in the construction environment or mega infrastructure construction-environment compound system. Whether the disasters are natural or man-made, managing potential disasters is a complicated issue for mega infrastructure construction site management (Blaikie et al. 2014).

In general, the cause, effects, and evolution of natural disasters all follow independent natural laws and are characterized by large spatial and temporal scales. Therefore, the mega infrastructure construction management subject should, based on the objective natural laws, predict as accurately as possible the category, intensity, and scale of the various natural disasters likely to occur during the lifetime of the construction and, accordingly, develop disaster prevention and reduction plans during the early stages of decision-making and on-site and demonstrations. Such plans and decisions should take into consideration construction site selection, construction technology selection, construction scheme design, etc. (Li et al. 2015)

For instance, when building mega infrastructure constructions in volcanic areas that have a history of volcanic eruption and exhibit the possibility of future volcanic activity, prognostic maps of tephra falls, debris flows, and lahars should be developed to guide the work of site selection and disaster prevention in the mega infrastructure construction. For example, the construction cannot be located within the scale of tephra falls disasters. With respect to potential lahars, the destruction caused by the actual lahar must be considered, as should the possible chain disasters caused by the mudflows, such as potential flooding. Thus, it is necessary to establish an effective monitoring and alarm system in the relevant areas and implement emergency forewarning techniques of occurrences of, for example, reservoir drainage (Liu and Liu 2005). In areas where strong earthquakes once occurred, it is necessary to predict the occurrence rates, epicenter intensity, occurrence areas, occurrence times, and developmental direction of later aftershocks to determine which areas should be avoided when selecting construction sites.

There are also several types of man-made disastersc at mega infrastructure construction sites.

One such type is the disasters caused by decision errors during mega infrastructure construction. This type of disaster is particularly reflected by the induction of a mega infrastructure construction-environment compound system and includes both natural and ecological disasters over the long lifetime of the construction. For example, geological disasters, downstream river swampiness, saltwater intrusions, soil salinization, and fish resource exhaustion are all caused by large-scale hydraulic engineering.

Another such type includes serious incidents caused by construction scheme design, key technology selection, low quality standards, and the triggered disastrous effects on the construction and surrounding areas, such as hydraulic engineering that causes the collapse of dams and tunnels. In particular, as man-made disasters increase the complexity of human behaviors, the complexity of disaster prevention and reduction at construction sites also increases.

2. Principles of managing disasters in mega infrastructure construction site

The guiding principle of managing disasters for mega infrastructure construction site management is to prevent and reduce disasters. The concept of preventing disasters incorporates prevention and caution. However, because it is generally difficult to prevent large-scale serious natural disasters, it is necessary to adopt the philosophy of precaution, that is, to take preventive measures to guard against potential disasters. Such measures and preparation can relieve, reduce, and lessen the loss from disasters. Disaster reduction suggests that during the constructing process of the mega infrastructure construction site, due to the precautionary measures, the loss from a disaster once it occurs is reduced. Therefore, whether it is disaster prevention or reduction, its fundamental purpose is to reduce the effects caused by disasters, and the practical way to accomplish this is either to reduce the possibility of the occurrence or reduce the loss suffered after the occurrence. Thus, the general principle of mega infrastructure construction with respect to disasters is comprehensive disaster reduction, which means to develop a comprehensive disaster prevention and reduction plan and to ensure comprehensive disaster reduction management.

In summary, there are three fundamental principles regarding potential disasters that mega infrastructure construction site management must adopt:

(i) To reduce, to the greatest extent possible, the possibility of the occurrence of a disaster based on respecting the objective natural laws. Once a disaster occurs, the scale and damage caused by the disaster can be effectively reduced by the precautionary measures implemented in advance.

(ii) Faced with natural disasters, man tends to believe that they are difficult to prevent. Thus, the focus should be on reducing the loss caused by the disaster by establishing a comprehensive disaster reduction site management system in advance and developing the requisite disaster reduction plans (Park et al. 2016).

(iii) If (i) and (ii) are combined, the management core of site disaster prevention and reduction should be to incorporate and implement whole process, all-dimensional disaster reduction management by applying various comprehensive methods and techniques.

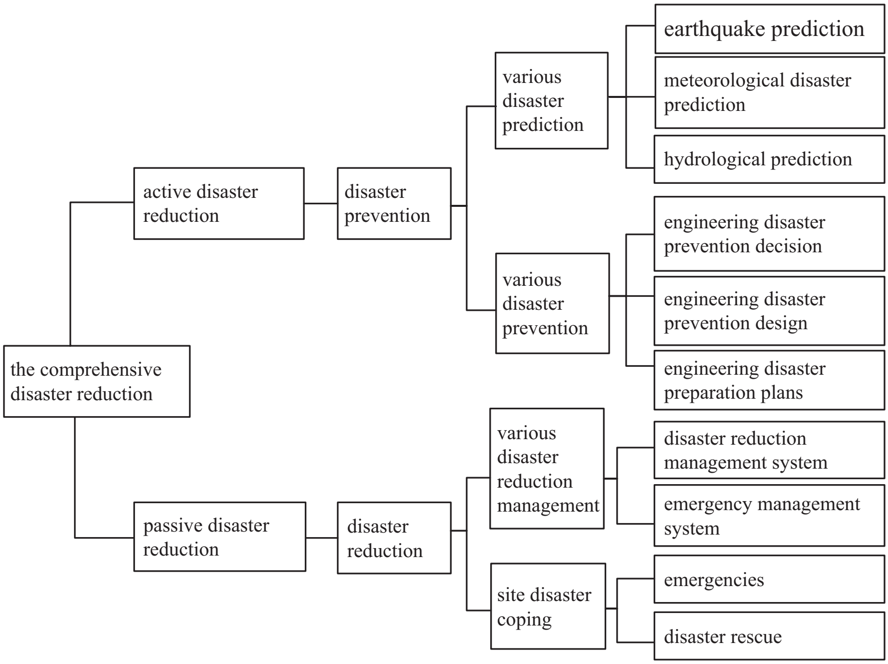

Fig. 7.18 The connotative structure chart of comprehensive disaster reduction at the mega infrastructure construction site (Cui 2006)

Cui (2006) has studied the importance of civil engineering in disaster prevention and reduction and inspired by this study, a connotative structure chart of comprehensive disaster reduction at the mega infrastructure construction site has been constructed and is presented in Fig. 7.18.

It is evident that whether it be active disaster reduction, i.e., prevention, or passive disaster reduction, the execution and implementation of all measures are reflected in the subjects' disaster reduction behaviors at the construction site. Thus, comprehensive disaster reduction management at the mega infrastructure construction site is a scientific problem of important practical significance.

7.5.4.2 Comprehensive Disaster Reduction at the Mega Infrastructure Construction Site

Based on the previous discussions, an understanding of the scientific problem of comprehensive disaster reduction at mega infrastructure construction sites is possible.

1. A basic understanding of comprehensive disaster reduction at the mega infrastructure construction site

In general, disasters are a special type of scenario and phenomenon within the system, and as such, they are characterized by large-scale complexities and deep uncertainty. Therefore, mega infrastructure construction management site disasters differ from construction site disasters caused by physics engineering, local fault, and incidents due to management activities at the level of system elements or subsystems. In addition, to study mega infrastructure construction site disasters, its starting point cannot extend beyond the analysis of the disaster risks. As Murphy's Law states, "anything that can possibly go wrong, will go wrong sooner or later." Disasters are among the greatly wrongs that will go wrong sooner or later. Thus, comprehensive site disaster prevention must perceive low-probability disaster risks as inevitable disaster realities and, accordingly, explore how to manage them (Ismail et al. 2012).

Comprehensive disaster reduction in mega infrastructure construction is a process that extends throughout the lifetime of the construction. However, based on the chart (Fig. 7.18), the most important aspect is the pre-disaster precaution and the disaster reduction management during the construction phase at the construction site. More specifically, the former refers to designing relevant schemes for disaster prevention, and the latter refers to establishing a comprehensive site disaster reduction system.

2. A comprehensive disaster reduction system at the mega infrastructure construction site

A successful comprehensive disaster reduction system at a mega infrastructure construction site is multidimensional and a whole process technique. As such, it is required that it be a solid and complete organizational system that can guarantee and form a stable, multifunctional, comprehensive disaster reduction security system of (Chen 2009; Ding et al. 2013).

Such a system will consist of several subsystems:

(i) A comprehensive disaster reduction system is dependent on a functional organization whose task is to ensure comprehensive disaster reduction at the construction site. Moreover, it is a reasonable and efficient scientific system that is both horizontally and vertically aligned. Horizontal coordination is necessary because comprehensive disaster reduction at the mega infrastructure construction site involves many subjects and sectors. Only by realizing the interrelationships and operation of all parties can the ability of a comprehensive disaster reduction plan be formed and optimized. Vertical command guarantees the effective, orderly, and efficient implementation of the various tasks of the comprehensive disaster reduction plan in emergency circumstances.
(ii) The system of responsibility with respect to comprehensive disaster reduction allocates disaster reduction responsibilities to all subjects at the construction site and defines the conduct of all tasks associated with the comprehensive disaster reduction plan. In this system, there are five functions, namely, decomposition and implementation of disaster reduction responsibilities; execution of the responsibility system, supervision, and inspection of the responsibilities; assessments and rewards and punishments for performing the responsibilities; and accountability and investigation regarding the responsibilities.

(iii) The institutional system of comprehensive disaster reduction is comprised of numerous facets. In view of the large-scale complicated technologies at the mega infrastructure construction site, to conduct the requisite work of comprehensive site disaster reduction in an orderly and effective way, reduce conflicts, and improve coordination abilities, all subjects at the site should restrain from engaging in behaviors that are contrary to the rules of the relevant institutions, should comply with the regulations as the relate to disaster reduction, and should develop positive collaborative relationship with each other, all of which lend themselves to creating an institutional system of comprehensive disaster reduction at the construction site.

(iv) The educational system of comprehensive disaster reduction adopts various educational forms and methods, firmly implants the comprehensive disaster reduction philosophy of people first, improves the comprehensive disaster reduction awareness of personnel, and facilitates their mastery of the relevant disaster reduction technologies. The implementation of an educational system focused on comprehensive disaster reduction can prevent the occurrence of man-made disasters, improve the self-rescue abilities of personnel, and reduce personnel and property loss once a disaster occurs (Shin et al. 2014; Zhu et al. 2016).

(v) Regardless of how complete a disaster prevention system at a mega infrastructure construction site is, it is still possible that natural or man-made disasters will occur. Therefore, it is important to focus on the work of emergency rescue after a disaster occurs, especially the development of emergency plans for sudden onset disasters. The emergency plan system includes the creation of an organized emergency plan that defines the process management, emergency resources, and emergency drills (Tsai et al. 2016).

3. Actual cases

Case 1: The design of a disaster prevention scheme for the construction site of the Su Tong Yangtze River Highway Bridge

The Su Tong Yangtze River Highway Bridge of China is located at the mouth of the Yangtze River. The river surface is 6000 meters wide, the flow is rapid, the waves are one to three meters high, and the tidal range is two to four meters. The meteorological conditions are poor, with frequent natural disasters such as typhoons, monsoons, and tornados. The navigation density of the bridge zone is large, with an average of over 2500 vessels per day and 6000 vessels during rush hours. Among these vessels, several hundred are in the over 10,000 ton class. The bridge zone has a high potential for man-made disasters.

With respect to natural disasters, the construction design of the Su Tong Yangtze River Highway Bridge exhibits sufficient disaster prevention. As a result, the bridge can resist earthquakes below 8 M. During the demonstration stage of the scheme, strict wind tunnel simulation experiments were conducted, and the bridge was capable of resisting ten classes of typhoons. The safety factor exceeds twice the standard limits. The bridge tower is equipped with windbreak and guide plates to reduce the impact of strong winds.

After the bridge was completed, the bridge zone was open to 50,000 ton container ships and, under specified conditions, 200,000 ton oil tankers. To prevent man-made disasters caused by ship collisions, the bridge has been equipped with active and passive collision avoidance systems. The active collision avoidance system involves controlling the course and speed of the ship through auto control technology to prevent the ship from approaching the bridge pier and having a collision. Passive collision avoidance required the addition of a round of shock elimination facilities around the bridge to protect the bridge pier from mass destruction in the event of a collision.

During the construction period of the bridge, conflicts between site construction and navigation were particularly prominent, and the occurrence probability of man-made collision disasters suddenly increased. The preparation files for preventing such disasters are extremely detailed.

(i) Analyses should be conducted to determine the monitoring range of an out-of-control ship at the project construction site.
(ii) Efforts should be made to strictly execute the reporting system when large ships pass the construction site of the bridge zone, monitor the passing ships and ensure that they strictly follow the lane regulations, transit the dynamic present situation to the bridge through the VTS system, and conduct all-weather monitoring and install collision avoidance and energy dissipation facilities around the bridge pier.
(iii) When an out-of-control ship has been confirmed, it is necessary to immediately execute the emergency plans, conduct a comprehensive rescue of the ship, remove the ship from the waters adjacent to the bridge, and move it to safe waters for anchoring.

Case 2: A study on the reduction of fire disasters in the tunnels of the Hong Kong-Zhuhai-Macao Bridge

The Hong Kong-Zhuhai-Macao Bridge of China is a sea-crossing tunnel-island-bridge cluster project. As such, there is a 6.7 km long offshore, deep-water immersed tunnel. There are several factors that make it difficult to enact a comprehensive site disaster reduction plan:

(i) The joints of the immersed tunnel, the mechanical behaviors of a structural fire, and the implementation of fire-resistant protection technology are challenges that must be overcome to facilitate the reduction in loss caused by a disaster.
(ii) The incorporation of fire prevention detection technology is difficult within such a structure, i.e., it is a long, offshore deep-water immersed tunnel.
(iii) The inclusion of fire alarms and fire extinguishing technologies as well as the collocation method of safety precaution facilities is also challenging given the characteristics of the structure.
(iv) The laws governing fire smog fields, temperature fields, and pressure fields are difficult to enforce within such a system.
(v) Innovative methods and technologies to evacuate smoke and properly ventilate the structure are necessary.
(vi) A comprehensive system to evacuate and rescue personnel must take into consideration all of the complexities of the structure.

These above problems are both technological and managerial, and they include both physical problems related to construction as well as problems involving human behaviors. Therefore, to analyze and resolve these problems, it is necessary to integrate multidisciplinary technologies and methods, intensify and emphasize disaster prevention, and develop comprehensive plans. Accordingly, it constitutes a typical issue related to comprehensive disaster reduction at a mega infrastructure construction site.

With respect to solving such disaster problems at mega infrastructure construction sites, there is a lack of experience and a lack of examples. Therefore, because it is also difficult to deduce solutions and actions based on pure theoretical analysis and mathematical models, an alternative option is to conduct a site simulation test.

With respect to the study of reducing fire disasters in immersed tunnels, a full-scale comprehensive test platform for tunnels is established, and tunnel fire scenario tests are conducted. The chief purpose of these tests is to distinguish the sources of danger, predict potential fire disasters, and identify the serious consequences of such fires. This includes assessing the different fire control mechanisms and plans as well as the disaster relief schemes according to the different types of fire environments and scenarios.

Based on the numerous test results and theoretical analyses, comprehensive plans for disaster reduction at the construction site have been establishment, such as the security level standards for the rather long immersed tunnel, the collocation of the security facilities, and the effective extinguishment technologies.

Regardless of the type of disaster, the first goal of a comprehensive disaster reduction plan is to save the lives of the people. Therefore, in the above tunnel fire disaster relief plans, the main factors that influence or contribute to personnel evacuation behaviors in immersed tunnels, such as construction ontology, fire disaster, conditions, and management, have been thoroughly analyzed. Among them are the factors related specifically to the physics of construction in an underwater environment, such as tunnel length, evacuation routes, and the intervals between and the widths of evacuation exits.

Further empirical investigation and experimental results indicate that age, gender, and educational level have remarkable effects on the mentalities and behaviors of personnel during evacuation procedures. Statistical analyses further find that when a tunnel fire occurs, most people exhibit poor psychological reactions. For example, women are less rational than men, and people with higher educational levels exhibit higher degrees of panic. When a fire occurs, people's psychological reactions, such as fear, panic, impulsivity, solitude, and conformity, greatly affect their behaviors during evacuation and are closely related to refuge behaviors. Thus, detailed features such as velocity distribution and escape routes for personnel during evacuating procedures in immersed tunnels must be determined.

To master and successfully implement the appropriate behaviors, information and automation are needed to create the plans for personnel evacuation and emergency relief when a fire disaster occurs in the undersea tunnel of the Hong Kong-Zhuhai-Macao Bridge (China Merchants Chongqing Communications Technology Research & Design Institute Co., LTD., 2015).

Based on the cases discussed, it is evident that to study disasters at mega infrastructure construction sites, it is necessary to apply the principle of complex thinking, scientifically distinguish between the features of natural disasters and man-made disasters, and accordingly adopt the appropriate policies and methods. To identify the appropriate policies and methods, an analysis of the combination of the comprehensive disaster reduction plans, risk management, and security control should be conducted. The most important strategy to be adopted by management is prevention first. However, due to the deep uncertainty of the disaster risks and the complexity caused by the horizontal strong correlation on site, people should, when faced with disasters, understand and accept that disasters are difficult to prevent; thus, under the guidance of comprehensive disaster reduction, they should implement pre-disaster prevention and disaster reduction management.

7.6 Risk Analysis and Control of the Complexity of Mega Infrastructure Construction

In the practical creation of mega infrastructure construction, a wide range of uncertain and potential dangers and disasters will inevitably result in risks to mega infrastructure construction (Han et al. 2005; Jennings 2012; Serpella et al. 2014; Wang and Chou 2003).

Compared with general construction, the uncertainty of being at risk increases dramatically for mega infrastructure construction. Furthermore, once the disaster occurs, the dangers and damages to mega infrastructure construction are much greater than those uncured by general construction (Ansar et al. 2014; Ebrahimnejad et al. 2014; Flyvbjerg et al. 2003b; Hwang et al. 2014). In particular, some unique risk types formed by the complexity of mega infrastructure construction have new causes and formation mechanisms. In this regard, the cognition and treatment methods employed in general construction with respect to risks cannot be indiscriminately adopted by mega infrastructure construction. Instead, the complexity attribute of mega infrastructure construction must be considered when developing a cognition regarding risks in mega infrastructure construction, when identifying new and unique laws to address the risks, and when exploring new ways to control the risks.

Specifically, to study the scientific issue of the risks related to mega infrastructure construction, it is not sufficient to simply employ traditional risk research methods used in general construction, such as the analysis of risk sources, the probability estimation of risk occurrences, and the overall evaluation of relevant index systems. Rather, it is necessary to accurately analyze and study specific risks from the perspective of the complexity attribute of mega infrastructure construction (Choi and Mahadevan 2008; Wang et al. 2004; Yildiz et al. 2014). Accordingly, there are three types of unique risks that frequently occurred in practical mega infrastructure construction management as typical scientific issues with respect to risk analysis of mega infrastructure construction:

1. The decision-making risk to mega infrastructure construction (Falconer 2002; Kengpol and Neungrit 2014). Decision-making in mega infrastructure construction is an intricate management activity. Moreover, the decision-making environment is one of deep uncertainty. Therefore, the decision-making scheme exerts long-term and profound influence on both the construction itself and the socioeconomic environment. Any type of risk resulting from incorrect or wrong decisions may lead to severe consequences. Hence, it is necessary to increase the efforts to analyze and guard against decision-making risks.
2. The risk of overspending in mega infrastructure construction (Cantarelli et al. 2013; Flyvbjerg et al. 2003c; Jennings 2012). In reality, the final costs will exceed the initial budget in almost all mega infrastructure constructions. Because the investment in mega infrastructure construction is enormous and because the degree of the overspending amount is also substantial, follow-up investments will likely be made more often than not when the mega infrastructure construction is under construction, which can give rise to a series of financial, social, and political issues and may even result in abandoning a mega infrastructure construction in the midst of its development. People are not ignorant or think little of these phenomena; however, they often cite poor planning with respect to the disbursement of capital and the impact of an optimistic mood as reasons for the abandonment. It has been proven that these reasons are far from ideal when addressing the issue of the risk of overspending, and therefore, a risk analysis from a new perspective is necessary.
3. The site risk to mega infrastructure construction. In a sense, nearly all types of risks to mega infrastructure construction occur at the building site. Among them, some types of risks are consistent with the site risks of general construction, but others fully demonstrate the risk causes and unique mechanisms of the site complexity of mega infrastructure construction. Thus, it is necessary to develop a new concept and cognition of site risk as it pertains to mega infrastructure construction.

7.6.1 Analysis of the Decision-Making Risk in Mega Infrastructure Construction

Decision-making, particularly decision-making that involves the complexities of construction planning, project approval, and project demonstration, the overall planning in the preliminary stages of construction, and the selection of construction schemes, is a management activity of paramount strategic and overall importance (Hu et al. 2015; van Wee and Priemus 2006). Once a decision-making mistake is made, the danger caused will be far graver than that of localized and short-term accidents. Thus, as a consequence, a decision-making risk is a principal risk in mega infrastructure construction in terms of severity.

The decision-making risk in mega infrastructure construction refers to potential and uncertain dangers incurred by the decision-making process of mega infrastructure construction and by the decision-making scheme devised during this process throughout the entire life cycle of mega infrastructure construction. There are several issues that arise from this:

1. This type of danger is uncertain, i.e., it may or may not arise, and the likelihood of the danger occurring determines the likelihood of the occurrence of the risk.
2. This type of danger is a potential danger, and as such, it is a hidden danger, which makes it difficult to observe or predict in advance. If the ultimate potentiality does not become reality, it means that the risk was deterred.
3. This type of danger stems primarily from a wide array of people's behaviors during the decision-making process in mega infrastructure construction.
4. Because risk is uncertain, complete and certain danger cannot be deemed as risk as uncertainty or likelihood is one of the essential attributes of risk.

7.6.1.1 Overview of Decision-Making Risk

It is not uncommon, either at home or abroad, for improper decision-making to refrain from fulfilling the functions and objectives of mega infrastructure construction and, thus, for such decision-making to pose great danger to the socioeconomic and natural environments. This is a vivid warning of the existence and serious consequences of decision-making risks to mega infrastructure construction (Bedford 2013; Clemen and Reilly 1999; Flyvbjerg 2006).

With flood control as its main function, the Sanmenxia Dam Water Conservancy Project is the first multi-purpose, large-scale infrastructure water conservancy project ever established upstream of China's Yellow River. China has invested substantial amounts of manpower, material resources, and financial resources into this project. However, 1 year after its completion, due to incorrect decisions and design problems, the original objectives of the project had to be abandoned, and the project had to be reestablished. Even so, there still exists a sharp contradiction between the power generation of the reservoir and the sediment deposit in the upper reaches. In the autumn of 2003, the downstream Wei River in Shaanxi Province encountered a once-in-five-years small flood; later, however, it turned into a once-in-50-years large flood. According to the analysis of academics, the main reason was that the Sanmenxia reservoir operated at a high water level for so long and the Sanmenxia reservoir area in the lower reaches of Wei River was silted so severely that of the eight branches flowed backward and three of those burst. On January 4, 2004, Qu Geping, the president of the China Environmental Protection Foundation, stated in a news conference that the Sanmenxia project was a major decision-making mistake and a record failure among China's water conservancy projects.

The research on decision-making risks to mega infrastructure constructions can simply and intuitively center on decision-making activities of mega infrastructure constructions. They can then be classified, and list the risk sources one-by-one in accordance with the relevant elements:

1. The risk of demonstration and prediction. During the preliminary stage of mega infrastructure construction, it is required to predict and design the functions and objectives of the construction, for example, to predict the passenger flow for building a large airport. Once a major error occurs, it inevitably poses a risk to the construction. To use China's Zhuhai Airport as an example, it was so costly that merely the arrears of capital expenditures amounted to 1.7 billion RMB. After completion, the airport had a monthly passenger flow of 40,000 to 50,000 person-times, i.e., the equivalent of the daily passenger flow of Baiyun Airport of Guangzhou City. The passenger flow of the airport was designed and predicted to be 12 million person-times per year, but in fact, it was approximately 57,000 in 2015. Accordingly, the actual utilization rate was less than 1/24 of the predicted rate.
2. The risk of technological selection. The selection of key technologies for mega infrastructure construction requires not only the correct principles but also great maturity and robustness with respect to the technologies. However, the complexity of the actual environment and the uniqueness of the construction may result in the complete or partial malfunction of these technologies and, thus, the ultimate failure of the construction.
3. The risk of environmental changes. The decision-making regarding mega infrastructure construction occurs in an open environment during the preliminary stage of the construction activities and processes at the level of construction insubstantiality. Consequently, the decision-making subject's cognition of construction insubstantiality and the presupposition and idealization of the environment profoundly influence the effectiveness of the decision-making scheme of mega infrastructure construction. Once the sharp contradiction between environmental changes and the effectiveness of the decision-making scheme arises, the risk of wrong decision-making necessarily emerges.

However, there are many other instances. By decomposing the decision-making activities of mega infrastructure construction one-by-one, a series of decision-making risks to mega infrastructure construction emerge. This decomposition process is frequently applied to analyze the risks of specific constructions. However, based on the essential attribute of complexity, studies on the decision-making risk to mega infrastructure construction from scientific issues are the primary focus herein. Thus, the emphasis is not the method of listing the sources of the decision-making risks but about the analysis of the risk associated with the decision-making process posed by the complexity of decision-making behaviors.

7.6.1.2 The Risk of the Decision-Making Process in Mega Infrastructure Construction

Because the decision-making risk in mega infrastructure construction stems from the decision-making activity of the construction and because any decision-making activity is composed of the decision-making process and its results, the decision-making risk is determined by both the decision-making result and the quality of the decision-making process. This is analogous to the making of products in that the quality of the product not only depends on the product itself but on the quality of the production process.

In this way, the decision-making scheme is the product of the decision-making subject created during the decision-making process. Thus, the higher the quality of the decision-making scheme is, the lower the risk of the decision-making activity is. Accordingly, based on the concept of the quality of decision-making, by revealing that the decision-making of mega infrastructure construction is characterized by deep uncertainty, the core connotation of the quality of the decision-making scheme is the scheme's robustness regarding the change and evolution of the construction scenario (as noted in Sect. 7.2). Based on this academic thought, it is evident that scenario robustness can be regarded as a crucial attribute for predicting, assessing, and identifying the decision-making risk to mega infrastructure construction.

In addition, because the decision-making scheme of mega infrastructure construction is the ultimate product of the decision-making process, the decision-making scheme is highly dependent on the scenario. That is, to understand and analyze the decision-making risk to mega infrastructure construction, the impact of the decision-making process of mega infrastructure construction on the formation of the risk must be analyzed, so countermeasures that promote the quality of the process and reduce the decision-making risk can be proposed.

In accordance with the definition of ISO9000:2000, process refers to a set of interrelated or interactive activities that transform input into output (Chin and Choi 2003). The decision-making process of general construction can be considered as a set of activities that raise questions, analyze questions, and propose solutions. The core content of this type of decision-making process is contained within the specific decision-making procedures or steps. Because the decisions of the decision-making subject of general construction remain unchanged throughout the process, the decision-making environment, the formation of objectives and alternatives, and the selection of schemes are relatively simple; therefore, the main task of the decision-making process is to complete each step of the process consistent with the identified procedures.

However, owing to the complexities of the decision-making environment, the problems in mega infrastructure construction and the iterative pattern through which the decision-making objectives and schemes are formed, particularly the sociability and self-adaptability of the decision-making subject's behavior, the decision-making process of mega infrastructure construction can no longer be understood as a set of activities consisting of normative and procedural steps, but rather, it should be understood as a behavioral chain of a self-adaptable organization that is composed of multiple subjects and a complex system with a flexible structure. This means that the decision-making process of mega infrastructure construction is composed of numerous complexities, some of which emerge as the ability to manage complicated decision-making problems, while others may lead to the formation of risks related to the decision-making process.

More simply, *the risk associated with the decision-making process in mega infrastructure construction refers to the likelihood of posing potential danger to the construction as a result of the decision-making subject's behavior during the decision-making process.*

This means that the risk of the decision-making process must have a corresponding carrier of the subject's activity or behavior. Accordingly, it is the overall results of these activities or behaviors that lead to the dangers of these risks.

7.6.1.3 Two Typical Types of Risks Associated with the Decision-Making Process of Mega Infrastructure Construction

(1) *The Risk of Information Monopoly*

Those familiar with the decision-making activities of mega infrastructure construction realize that decision-making is based on data and information. According to the objectives and requirements of decision-making, people collect as much relevant data and information as possible and then appropriately analyze those data to obtain the necessary support and basis for establishing a decision-making scheme. Accordingly, this represents a process of information processing and transformation that runs throughout the decision-making activity. Thus, it is evident that given more comprehensive information, decision-makers make better and more accurate decisions, whereas a lack of information results in incorrect decisions or gives rise to inferior decision-making schemes. Moreover, the behavior of concealing or distorting information is more likely to incur decision-making risk. Hence, it is necessary to apply complex thinking to comprehensively examine, thoroughly study, and accurately assess the decision-making subject's attitudes and behaviors regarding the access to information during the decision-making process and to guard against potential risks.

During the decision-making process of mega infrastructure construction, the government or its agent generally has the advantage of possessing information. In this scenario, considering national security and social stability, it is a normal behavior for the government to keep certain information secret. However, there are times when the nontransparency, asymmetry, or even the monopoly of information may be due to excessive information secrecy or times when the information possessors try to maintain their own images or purposely isolate the public from the information related to decision-making for their own good. Apart from that, the decision-making subjects may opt to disclose only the information from which they can benefit, or they may even deliberately delete or distort ordinary information to attain wrongful goals, thus leading to a definite wrong decision-making scheme and to a situation where problems are even more severe.

If any of the above cases appear, the decision-making process of mega infrastructure construction can only be implemented when information loss and distortion occur and the likelihood of the decision-making risk occurring is greatly increased.

This is referred to as *the risk of an information monopoly in the decision-making process of mega infrastructure construction*.

Accordingly, there exist cases where the decision-making subject does not resort to an information monopoly to seek interests but where their inability to collect, manage, and use information can result in information loss and, thus, decision-making mistakes. A problem of another nature is that it also belongs to decision-making risks incurred by information loss.

Since information risk may be associated with the decision-making process of mega infrastructure construction, a better understanding of the basic features of information risk is needed to more effectively prevent such risk.

First, there are various forms of risks during the stages of information collection, identification, processing, and analysis. For example, information loss, information redundancy, information disorder, and even information conflict are all risks. Though great importance has been attached to the value of information, the value varies according to time, place, and objective. Thus, it is too dogmatic to think that the value of information remains constant and unchanged. Using the Sanmenxia reservoir as an example, in those years, the Soviet experts involved in the decision-making of projects designed the Sanmenxia project based on their own experience, knowledge, and information, regardless of the fact that Soviet rivers were basically clean rivers, whereas China's Yellow River was a sediment river. In this context, the indiscriminate copying of original knowledge and information results in decision-making mistakes.

Furthermore, because information is often highly time based, it reflects the objective properties of entities within a certain period of time. Thus, attention should be paid to whether the information applied to the decision-making process of mega infrastructure construction is out of date, and if it is, relevant information should be carefully employed.

In addition, besides being direct and visible, information risk may be indirect and invisible and present a long association of conductivity. For instance, information deviation may not pose an immediate risk, but its influence and effect will be gradually exposed over time, thus making it difficult to trace the source of the risk. This situation, to a great extent, reflects the complexity of information risk.

To prevent and control information risk during the process of mega infrastructure construction, emphasis should be on establishing and improving relevant democratic and legal systems. For example, an information disclosure system for mega infrastructure construction is cited as a necessary development.

To manage the decision-making risk during the decision-making process of mega infrastructure construction arising from information asymmetry and to earnestly ensure the information interaction between the construction decision-makers and the public, it is necessary to establish and improve the information disclosure system for mega infrastructure construction. On the one hand, the system creates conditions whereby the public can actively participate in the decision-making process of mega infrastructure construction and can present ideas and suggestions. On the other hand, the system provides a platform for the public to supervise the decision-makers throughout the decision-making process to guard against the decision-making risks incurred by an information monopoly and to promote a standardized, procedural decision-making process of mega infrastructure construction.

The decision-making process of mega infrastructure construction is a process of constant comparison, iteration, and optimization that ends with a final decision-making scheme. During this process, the interim schemes of each stage must have information basis and support. For this reason, it is necessary to establish legal, open, and transparent procedures and to enable both experts and representatives of the public to participate directly in the supervision and evaluation of information based, in some way, on key schemes to prevent and correct information deviation in a timely and effective way.

(2) *The Risk of Behavior Variation*

The core behavior of the decision-making subjects involved in the decision-making process of mega infrastructure construction is their selection. Thus, the decision-making subjects' selection reflects their ability to analyze and control the complexity of the decision-making process, which relies strongly on their intelligence, such as their perceptions, cognitions, experiences, and knowledge, their understanding of the essence of the complexity of the issues, their strategic thinking regarding the situation for integrating decision-making resources, and their overall evaluation and risk analysis of the functions and objectives of decision-making schemes. However, there is a basic premise for this series of behaviors. That is, the decision-makers must observe the rules and regulations of the decision-making process under the standards and basic code of conduct.

However, on the one hand, any decision-making subject involved in the mega infrastructure construction is a social person in a principal-agent relationship who has his own interests or represents the interests of others and will adequately safeguard these interests throughout the decision-making process. On the other hand, during the actual decision-making process, owing to an imperfect principal-agent system and the lack of supervision and management or owing to the agent's default and misconduct, the behavior variation may emerge when the decision-making subject seeks self-interests and damages the overall interests of the mega infrastructure construction. This type of decision-making risk, which results from the decision-making subject's breach of the code of conduct and the code of decision-making ethics during the decision-making process, is referred to as *the risk of behavior variation during the decision-making process of mega infrastructure construction*.

There are several reasons for the risks in behavior variation during the decision-making process of mega infrastructure construction. These include:

- Information monopoly or asymmetry as a loophole to be exploited by the subject
- A lack of sound systems and supervisory mechanisms
- The irrational boost of personal interest demand, such as the pursuit of personal political achievements, the working style of abuse of power, and the collusion of seeking illegitimate interests

These irrational personal actions cause decision-makers to quick success and instant benefits, abuse public power, and even abuse power for personal gains during the decision-making process. This may directly impact the decision-making process, a process that should be standardized and scientific and should feature no order, no procedure, and no excessive personal discretionary power, thus naturally incurring decision-making risk.

Similarly, to cope with and prevent the risk of behavior variation, it is necessary to strengthen and facilitate the establishment of relevant systems and regulations, particularly, a system for supervising key decision-makers, a strict system for selecting decision-makers, and an accountability system.

In general, whereas the decision-making subject's behavior variation is opportunistic, the risk is more subtle and intricate. For instance, the collusion to seek interests is always in private, but the behavior variation is often characterized by external camouflage, such as "The higher ups have policies, while the lower downs have their own ways of getting around them," "cry up wine and sell vinegar," and the "free rider problem." Hence, an in-depth study into the regularities of the types and causes of behavior variations is required as is an investigation of the more effective prevention systems and countermeasures against behavior variations.

In reality, the above two types of risks regarding the decision-making process of mega infrastructure construction often coexist in a project to varying degrees. Thus, an information monopoly and asymmetry provide favorable environments and conditions of shelter and camouflage for the decision-making subject's behavior variations, and the subject with behavior variations may take the initiative to create such environments and conditions. In contrast, such environments and conditions tend to catalyze and induce the subject's behavior variations. In this way, a versatile collaborative governance strategy should be applied to manage and prevent the risks of the decision-making process in mega infrastructure construction.

7.6.2 The Risk of Cost Overrun in Mega Infrastructure Construction

In mega infrastructure construction, other than its large scale and application of sophisticated technology, what draws people's attention is the frequent occurrence of cost overruns. Professor Flyvbjerg's research summarizes the nine types of characteristics shared by mega infrastructure constructions (Flyvbjerg 2011), and five of them have to do with cost overruns, thus indicating that cost overruns in mega infrastructure construction is a striking issue, imposing great risks on investments in mega infrastructure construction, and thereby exerting negative influence on politics, the economy, and society. Cost overruns in mega infrastructure construction have become an important phenomenon of risk and are an important scientific problem in the mega infrastructure construction management theory system.

7.6.2.1 Overview of Construction Cost Overruns

For many years, governments and scholars from different countries have been exploring the issue of cost overruns in mega infrastructure construction and have conducted systematic studies. Based on several surveys, Table 7.6 identified typical international construction cost overrun cases (part of the whole list) (Flyvbjerg 2007; Flyvbjerg et al. 2003a, b; Morris and Hough 1987; Szyliowicz and Goetz 1995):

Flyvbjerg et al. (2003a, b, c) analyzed the research of cost overrun of international projects conducted by the Auditor-General of Sweden, the U.S. Department of Transportation, the Transport and Road Research Laboratory in the U.K. and Aalborg University. The results are shown in the Table 7.6 (Flyvbjerg et al. 2003a, b, c). The research results indicate that (1) nine-tenths of mega transport infrastructure projects have cost overruns, among of which the average overrun for rail projects was 45%, for bridge and tunnel projects was 34%, for highway projects was 20%; (2) the overruns of mega construction projects are universally international phenomena and the issues in developing countries are more obvious than those in developed countries; (3) almost nothing changed or released about overruns in the past seventy years. Pedro, Pau and others conducted the statistic analyses of the typical overrun projects in Denmark, the U.K., Spain and other countries. It is shown in the Table 7.7.

The statistics show the following:

1. Cost overruns occur in 90% of the extremely large transportation system construction projects, with final costs increasing, on average, by 45% for railway constructions, 34% for bridges and tunnels, and 20% for highways.

Table 7.6 International construction cost overrun cases

Investigation	Case amount	Project type	Overrun amount	Note
Sweden Audit Bureau	15	Highway, railway	17% for highway, 86% for railway	Some projects remain unfinished at the time of the survey
US Department of Transportation	10	Railway	61	
UK Center for Transport Research	21	Underground system projects	6 have an overrun of 50%, 3 at 20–50%,and 4 at 10–20%	Overrun amount estimated for only 13 of the 21 projects
Aalborg University	258	Bridges, tunnels, highway, railway	28% (standard deviation = 39)	20 countries involved from 1927 to 1998

Table 7.7 Typical cost overrun cases in mega infrastructure construction

	Country	Project name	Type	Started in	Completed in	Budget	Overrun percentage
1	Denmark/Sweden	Oresund Strait Bridge[a]	Bridge	1993	2003	2.9 billion US dollars	39%
2	UK	The Channel Tunnel Rail Link[b]	Tunnel	1998	2007	6.1 billion US dollars	57%
3	Spain	Madrid-Seville Metro line[c]	Railway	2003	2009	0.46 billion euro	37%
4	Slovenia	Mochove units 3 and 4[d]	Nuclear power	2007	2014/2015	2.7 billion euro	33%
5	Germany	Kraftwerk-Moorburg coal-burning power plant[e]	Coal burning power	2006	2014	1.8 billion euro	67%
6	France	Flamanville unit 3[f]	Nuclear power	2006	2016	3.3 billion euro	82%
7	Denmark	Anholt Offshore Wind Farm[g]	Wind power	2011	2013	1.32 billion euro	74%
8	Czech	Brno City circuit road[h]	Highway	1998	2035	0.34 billion euro	24%
9	Spain	Madrid-Seville Metro line[i]	Railway	1987	1993	1.575 billion euro	72%
10	Portuguese	Portuguese high-speed railway[j]	Railway	2003	2012	6.5 billion euro	28%
11	Spain	Spanish high-speed railway[k]	Railway	1995	2009	7.9 billion euro	80%

12	Germany	Nuremberg-Ingolstadt high-speed railway[l]	Railway	2003	2006	1.368 billion euro	161%
13	Sweden	The Northern Link[m]	Tunnel	2010	2019	0.16 billion euro	15%
14	Germany	Nowy Tomysl-Swiecko expressway[n]	Highway	2006	2012	0.646 billion euro	57%

Sources:
[a]Pedro and Mikic (2015b)
[b]Pedro and Mikic (2015a)
[c]Irimia-Dieguez et al. (2015)
[d]Špirková and Ivanička (2015)
[e]Adlbrecht et al. (2015)
[f]Locatelli and Mancini (2015)
[g]Pau (2015)
[h]Korytárová et al. (2015)
[i]Alfalla-Luque and Medina-López (2015b)
[j]de Abreu e Silva and Pedro (2015)
[k]Alfalla-Luque and Medina-López (2015a)
[l]Spang and Kümmerle (2015)
[m]Wennström and Länken (2015)
[n]Łukasiewicz (2015)

Table 7.8 Typical cost overrun cases in Chinese large bridge constructions (unit: 0.1 billion RMB)

No.	Project name	Estimate	Budget	Final cost	Overrun (%)	Source
1	Langqi Bridge over Minjiang River (琅岐闽江大桥)	19.60	–	22.56	15.10	Project approval document and interview with Fujian Province's Ministry of Transport
2	Aizhai Bridge (矮寨大桥)	7.20	–	15.00	108.33	Project approval report and China's first military portal website
3	Jiangyin Bridge (江阴大桥)	–	20.87	27.30	30.82	Approval document from Ministry of Transport and related final report
4	The Second Nanjing Yangtze River Bridge (南京长江二桥)	–	32.00	33.50	4.69	Xinhua Daily and the second bridge website (二桥网)
5	The Third Nanjing Yangtze River Bridge (南京长江三桥)	–	30.90	31.87	3.14	*Management of Constructing Nanjing Yangtze River Bridges in a New Era* (新时代南京跨江大桥建设管理》) and the website of China auditing (中国审计网)
6	The Fourth Nanjing Yangtze River Bridge (南京长江四桥)	–	66.00	68.60	3.94	Xinhua Daily and Modern Express (现代快报)
7	Su Tong Yangtze River Highway Bridge (苏通大桥)	–	64.50	80.00	24.03	Interview with Hong Kong-Zhuhai-Macao Bridge Authority
8	Taizhou Bridge (泰州大桥)	89.90	–	93.70	4.23	Project approval report and www.people.cn/Jiangsu
9	Jiaozhou Bay Bridge (胶州湾大桥)	–	90.40	100.00	10.62	Interview with Shandong Province's Ministry of Transport
10	Hangzhou Bay Bridge (杭州湾大桥)	–	117.60	134.50	14.37	Acceptance report
11	Jiaxing-Shaoxing Bridge (嘉绍大桥)	–	62.50	63.50	1.60	Summary report from the directing unit and online Jiaxing news
12	Xiamen Zhangzhou Bridge (厦漳大桥)	30.00	–	47.10	57.00	Project approval report and interview with its managing company
13	Longjiang Bridge in Tengchong, Yunnan (云南腾冲龙江大桥)	–	14.60	18.00	23.29	Interview with the directing unit
14	Man'anshan Bridge (马鞍山大桥)	–	60.00	70.80	18.00	Interview with Anhui Transportation Holding Group (安徽高速公路控股集团) and document prepared by the bridge's directing unit
15	Nanpu Bridge (南浦大桥)	–	14.00	21.50	53.57	Interview with Shanghai Railway Bureau
16	Xupu Bridge (徐浦大桥)	7.30	–	20.00	173.97	Interview with Shanghai Railway Bureau
17	Yangpu Bridge (杨浦大桥)	13.20	–	14.53	10.08	Interview with Shanghai Railway Bureau
18	Shanghai Donghai Bridge (东海大桥)	–	70.00	110.00	57.14	Interview with Hong Kong-Zhuhai-Macao Bridge Authority

2. Cost overruns in mega infrastructure construction are an international phenomenon, and the problem is more serious in developing countries than in developed countries.
3. The cost overrun situation has not improved in the last 70 years (Table 7.7).

Similarly, cost overruns are also striking in Chinese mega infrastructure constructions. Typical cases are presented in Table 7.8.

Cost overruns are so common in mega infrastructure constructions, and the difference between real costs and estimates is so huge that investors, especially governments, must constantly increase the budget, bringing about waves upon waves of suspicion and criticism from the public. Therefore, the overrun issue has attracted broader social concern and attention from experts.

The cost overruns are caused, according to experts from both the academic circle and practical sites, by the complexity of a project, alterations, and uncertainties in technology, demand, and environment. For the overrun cases listed in Table 7.8, experts identify several causes (Ansar et al. 2014; Flyvbjerg 2006, 2011):

1. Bad luck or errors
2. Overly optimistic decision-makers
3. Misleading strategies
4. Changes in project scope, unfavorable criticism, etc.

With respect to the cases in China, Chinese scholars have also identified several causes (Wang et al. 2008):

1. Variations
2. Increased compensation and other fees for land use, house removal, and resettlement
3. Increased price of goods

From the above, the following conclusions can be drawn:

1. Cost overruns in mega infrastructure constructions are common phenomena with a long history worldwide.
2. The reasons for cost overruns are of various types and are quite different from one another.
3. It is difficult to predict possible reasons for overruns in a new project and difficult to predict the exceeded amount based on statistics from collected samples.

Accordingly, although the cost overrun phenomenon can be explained on a macro level, no statistics can be used to reveal the patterns behind it. It is also evident that cost overruns are probably dictated by the natural complexity of mega infrastructure construction, suggesting that it is necessary to analyze the phenomenon under the guidance of the complexity thought principle.

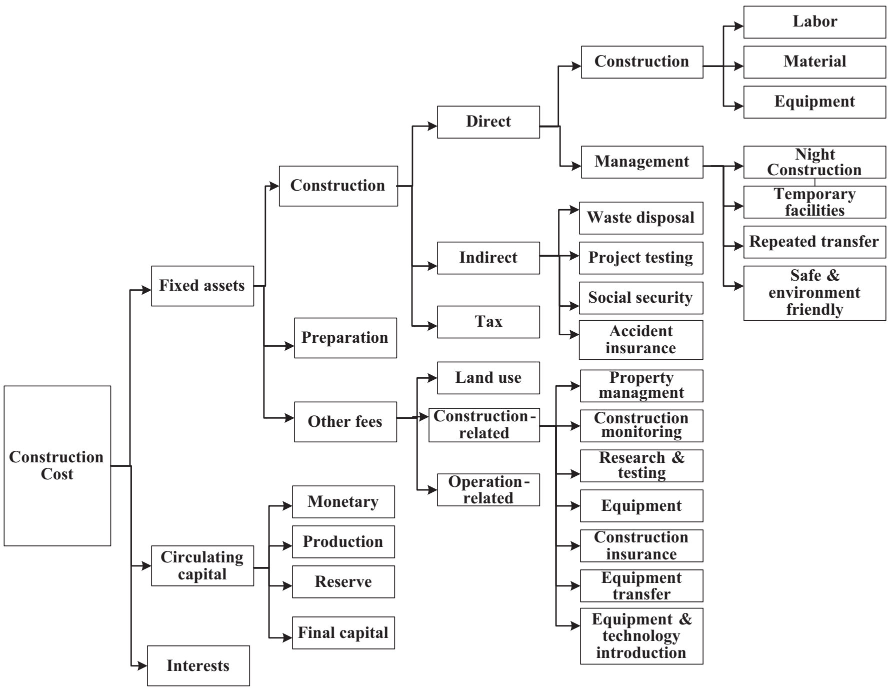

Fig. 7.19 Breakdown of construction costs for work

7.6.2.2 Understanding the Relation Between Cost Overruns in General Constructions and Optimism Deviation

When analyzing cost overruns in mega infrastructure constructions, the problem approached should by first examining the concept of construction cost. Construction cost refers to the amount of money necessary and indispensable to the completion of a construction, and accordingly, two points are of value.

1. Cost is the total sum of money for all activities necessary for the completion of a project. All activities refer to every indispensable activity that occurs.
2. Cost, as a necessary investment, excludes any money arising from waste or corruption.

Based on those two points, the cost for general constructions is first decomposed, which means to decompose the construction activities into smaller ones and examine all the elements that contribute to total cost (see Fig. 7.19). Then, based on the construction load, price, and resource consumption of the sub-activities, the costs are estimated and the numbers are added, thus yielding the total cost.

Reductionist thinking, as reflected in this decomposition process, indicates that constructions, overall, are perceived as knowable, completely invariable, and equal to the combination of their constituent parts. That is, the whole construction activity can be decomposed, layer-by-layer, into separate units, and the cost for each unit can then be calculated. Such a thought pattern can be applied to constructions that are generally short and involve comparatively simple and invariable environmental and technological factors because general constructions are basically invariable and are conducted according to certain procedures. Thus, the costs can be calculated.

This, however, does not mean that the calculation is accurate or exact as there is a difference between real costs and estimates because, for general constructions, the construction environment, construction operations, technological effects, and subjects' behavior often change. Furthermore, there may even be deviations and errors, in which case, the cost, in reality, often increases, causing cost overruns. It is far more often the case that the real costs increase rather than decrease because, when estimating the costs, the construction is decomposed as if it were a virtual construction in ideal conditions, and therefore, the calculations are based on experiences and on considering the obvious activities that are invariable and conducted according to procedures. In so doing, the hidden activities that are variable and occur not according to procedures are ignored, which results in shrinkage to the estimate of construction cost. This means that the real cost generally exceeds the estimate. Thus *cost overruns* occur frequently, but *cost reduction*s are rare.

As previously mentioned, the following conclusions regarding cost overruns in general construction projects are proposed:

1. Cost overruns are common in general construction projects.
2. For each sub-activity, comparing the real cost with the estimated cost reveals which activities resulted in cost overruns occur and the amount of the overage. As such case studies increase, so, too, will the list of the overrun activities and the amount of the overage. The list, serving as a cost overrun database, indicates the reasons for overruns in certain types of construction, how frequent the overruns are and how large they are. This information is significant to better understand the overrun issue, summarize useful experiences in cost control, and better estimate the cost for new construction projects.
3. The list in (2) falls under the category of case study, as there is a lack of theoretical analysis of the scientific problem of cost overruns.

To bridge this theoretical gap, scholars have been conducting theoretical studies of cost overruns and have made substantial achievements. One such area is the relationship between optimism tendency and cost overruns in constructions, particularly mega infrastructure constructions.

Regarding the relation, Professor Bent Flyvbjerg has conducted important studies. In his article, *From Nobel Prize to Project Management: Getting Risks Right* (Flyvbjerg 2006), Flyvbjerg systematically advanced the concepts of optimism bias and misleading strategy and proposed that they are important because they cause people to overestimate the expected profits and underestimate the costs, thus leading to cost overruns. He also and proposed a new method for estimating costs, namely, referential estimates, which are aimed at reducing deviation arising from people's biases, including optimism bias and misleading strategy.

Flyvbjerg has continued to publish papers on the relation between optimism bias and cost overruns.

Rather than listing the direct causes of construction overruns after a construction is completed, Flyvbjerg approaches the overrun phenomenon from a theoretical perspective and investigates deeper reasons by analyzing the relation between man's psychological behaviors, rather than limiting himself to the immediate field of project management. The innovative studies have exerted great influence on the academic field of project management. Research indicates that there are, in practice, more than a few cases of cost overruns that have resulted from the subjects' tendency to be optimistic.

More importantly, Flyvbjerg notes that a person who lacks the knowledge, experience, and ability to make construction cost estimates, tends, due to his optimism, to underestimate the costs and overestimate the profits for *general constructions*, and especially for *mega infrastructure constructions*, though there are several exceptions. However, with complete and sound established procedures for analysis, evaluation, and peer review with respect to cost estimates, the loopholes and deviations during the estimating process should be identified and corrected. There is a concern that there so many cases and such substantial amounts of data indicating the frequent occurrence of cost overruns, without any sign that there is a reduction in the frequency of such cases. This suggests that the cost estimate experts in the field are not learning from their mistake as they continue to exhibit optimism bias. An ongoing case study that cross-examines the estimations of mega infrastructure construction costs by professionals and non-professionals indicates that they all exhibit optimism tendency, a behavior that lacks logical explanation.

In response to this, Flyvbjerg said, "Optimism tendency is not the primary and main reason for estimating too low the cost and too high the profit for mega infrastructure constructions. Optimism tendency may be part, but not all, of the reasons why cost overruns frequently happen" (Flyvbjerg 2006, 2011).

Flyvbjerg's comment about the influence of optimism bias on mega infrastructure construction cost overruns and their relationship, though scientifically correct, requires analysis.

First, optimism, reflected by an optimistic mindset, feelings, or spirit, is a concept that describes the human psychological condition and conveys a positive attitude, determined belief, and great confidence when a person is confronted with challenges or changes as a person's psychological condition reflects how he views objective things. Optimism, as a psychological condition, brings with it positive results and is a type of survival strategy as people continually develop and grow, because when an individual is optimistic about the future, he will be motivated to act (Phelps).

In this sense, optimism is a form of positive energy. Thus, whereas being optimistic is a positive trait, optimism tendency, optimism bias, and stubborn optimism cause people to be blindly optimistic; this causes them to underestimate difficulties, uncertainties, and risks and overestimate, with no evidence, expectations of profits and personal interests. Such a tendency results in the unconscious development of a habit to behave this way, and thus, when thinking about a problem, the unconscious habit gets in the way. For example, when estimating the cost for a mega infrastructure construction, people unconsciously activate their optimism tendency and thus underestimate the difficulties, risks, and costs while overestimating the profits, and the tendency, having become an unconscious habit, causes not accidental but systematic behavior deviations. This constitutes the fundamental meaning of optimism bias.

However, as Flyvbjerg noted, “Managers make decisions based on delusional optimism rather than on a rational weighting of gains, losses, and probabilities. They overestimate benefits and underestimate costs and time. They involuntarily spin scenarios of success and overlook the potential for mistakes and miscalculations. Optimism bias would be an important and credible explanation of underestimated costs and overestimated benefits in major project forecasting...Optimism bias may be part of the explanation of underperformance but does not appear to be the whole explanation” (Flyvbjerg 2011).

Furthermore, this opinion is in perfect accordance with the facts. To estimate the cost for mega infrastructure constructions is to make predictions, and in actual practice, there are predictions by individuals as well as by groups. Accordingly, individual predictions are influenced by the individual’s optimistic mindset, but not totally dictated by the individual’s psychological conditions as there are other important factors, such as the individual’s knowledge, experience, and ability. This is consistent with the fact that although a person exhibits few changes in his optimistic personality, he makes increasingly more accurate estimates as his experience and knowledge grows. In addition, group predictions and corrections are a result of a much more repetitive process whereby many more factors are considered, not simply due to the assumption that all group members have the same optimistic bias and that their bias can be added up and factored in while their knowledge, experience, prediction procedures, and other factors that influence the final predictions do not play a role. This assumption lacks the support of facts and theories. Moreover, as man’s psychological change follows a pattern, for those who are always optimistic, they experience regular changes with respect to the strength of their optimism. That is, there are times when people feel strongly optimistic, and there are times when their level of optimism is low—no one can always feel highly optimistic. This provides us with another perspective from which we can be convinced that optimism bias is not the fundamental reason for mega infrastructure construction cost overruns. After all, there is never the same tendency between the occurrence of mega infrastructure construction cost overruns and the regular changes of people’s optimistic feelings.

Furthermore, cognitive neurologists have found that the amygdala and the rostral anterior coagulate cortex (rACC) in the human brain have special functions, namely, the former has a documented role in the modulation of emotion whereas the latter modulates emotion and motivations by activating and reinforcing optimistic emotions. The stronger one’s feeling of optimism, the more active the two structures are and the closer their connection.

Therefore, it is beyond explanation that the two structures mysteriously become active when people who are separated by time, ethnicity, and culture make cost estimates regarding mega infrastructure constructions.

Instead, this phenomenon should be analyzed by using the two thinking modes in project management, namely, virtual project thinking and physical project thinking.

More specifically, even though it is ideally supposed that construction activities and related management activities are invariable and can be decomposed into different units, that is, it is supposed a construction is simple, the virtual project thinking that the main goal of cost estimation prior to construction is to form a blue print of the virtual project is still followed. Furthermore, during this process, people focus primarily on the general attributes of construction activities, the structure of hardware systems in the construction, the elements in and attributes of construction activities, and the relations among the elements while leaving out many more minute details. Therefore, under such a thinking mode, people make cost estimates within a loose framework that are based, to a large extent, on an ideal paradigm, without considering all of the setbacks, repetitions or even the possible complete do overs that often occur in reality.

Thus, when people come to the site, the virtual project blueprint becomes a physical one, all of the activities become more specific, and all of the details begin to appear one by one. At this point, all of the specific physical activities necessary for the completion of the construction have an associated cost, and at this time, the difference between the earlier loose estimations and the accurate sum of the costs for all of the activities becomes apparent as evidenced by an enormous increase in cost.

To summarize, general construction cost overruns occur often due to the deviations brought about by the virtual project thinking prior to construction and the physical project thinking during construction. The seriousness of these overruns depend on how loose the virtual thinking framework is compared to the one generated under the physical project thinking. The looser the framework within which objects and ideas are understood and analyzed the fewer the resources needed to accomplish them. Therefore, cost overruns are often a frequent occurrence, and the uncertainties behind the phenomenon constitute the risks of general construction cost overruns.

Fortunately, because it is comparatively easy to build up a cost structure system for general constructions, it is comparatively easy to control overruns in general constructions. Furthermore, these cost overruns are comparatively less serious due to the influence of rich experience and system analyses. In other words, cost overruns are less likely to occur in general constructions, but even if they do occur, they generally can be managed.

Finally, rather than analyzing the reasons for general construction cost overruns after listing them one-by-one, a thinking mode that can lead to a scientific understanding of the cost overrun issue is proposed. Then, once that understanding is formed, particular cost overrun cases can be analyzed, and the risks associated with the overruns can be studied in a more in-depth manner.

For the sake of convenience, the cost overrun phenomenon that occurs due to the simple addition of the costs for all sub-activities loosely decomposed from the entire construction project is called a *regular construction cost overrun,* and the risk that accompanies it is called a *regular construction cost overrun risk*. Generally, cost overruns in comparatively simple constructions are categorized as regular cost overruns, and the risk brought by such overruns are often viewed as regular overrun risks.

7.6.2.3 Mega Infrastructure Construction Cost Overrun Risks Due to Complexity

In a general sense, the way to understand and analyze cost overrun risk in general constructions can be applied to mega infrastructure constructions because mega infrastructure constructions are a type of general constructions. However, complexity, a critical attribute of mega infrastructure constructions, profoundly influences how overruns occur and what the risks are. Thus, it is necessary to focus on the rise to such unique phenomena and scientific problems.

One difference between general and mega infrastructure constructions is that the primary investor in mega infrastructure constructions is a government entity, and thus, the government entity often has the ultimate say in decisions and the final say in how to proceed with a construction. Accordingly, each step of the decision-making process requires the consideration of more political factors.

These political factors include political thinking and the pursuit of political interests. For example, to build a positive image of the government and improve the performance of certain officials, decision-makers want the construction to begin as quickly as possible. To this end, they exaggerate the significance of the construction or act to meet the will of the government. In so doing, they do not always exercise caution when making careful decisions about a construction project, or they change the design, intervene on the normal construction schedule, or twist the bidding procedure by exerting political power, which results in underestimating costs and ultimately leads to cost overruns. The entity designated by the government to evaluate the construction either directly adheres to the government's instructions or is influenced by the government's decision, thus causing the evaluators to also underestimate the cost. Lower costs often compel the public to believe that the government has made a great achievement, even though, in reality, there is no achievement at all.

In addition, because mega infrastructure construction occurs on a large scale, it involves sophisticated technology and has a comparatively long life cycle, all of which increase the seriousness of cost overruns.

Consider, for example, China's transportation system construction project. If the bridge is to last 100 years, the pier must be vertical with an error of no more than 1/100, but if the bridge is designed to last 120 years, the error, after calculation, must remain within 1/250, which requires the technological standard to be 2.5 times higher than the standard set for the 100-year bridge. Accordingly, this dramatic increase in technological standards will lead to a nonlinear increase in construction costs, as presented in Fig. 7.20.

In recent years, case studies have been conducted, and related literatures have been reviewed. Based on the findings, the types of events that account for cost overruns, such as increases in the costs of material, breakdowns of machinery, and revisions due to poor quality, have been identified and summarized. However, the analyses and investigations of causes reflect a thinking mode whereby only the surface is visible and in one overrun case after another, there is a failure to examine beneath the surface and find the most fundamental reason for the overrun. Therefore, this reductionist-driven analysis does not reveal what is beneath the surface even if

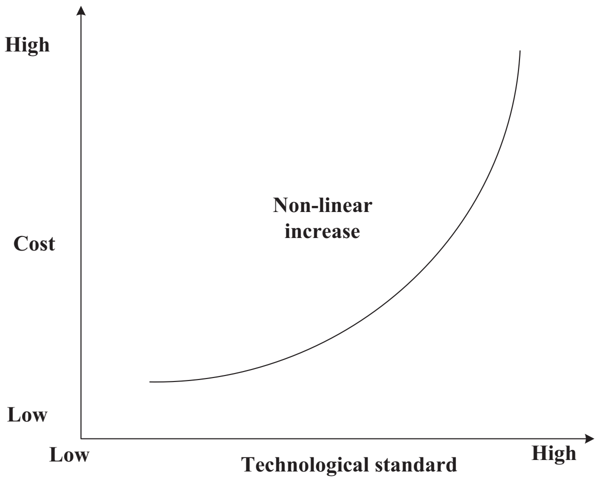

Fig. 7.20 The relation between costs and technological standards in mega infrastructure constructions

the cost element structure is developed. Thus, regardless of how detailed the cost element structure is, it includes only activities that are structural and are conducted according to the developed procedures. That said, in mega infrastructure constructions, events occur that are difficult to predict or control, though they dramatically expand the original planning scope and bring with them, one after another, new and unpredictable construction activities that are indispensable to the completion of the whole construction. The addition of construction activities means an unavoidable increase in cost, and thus, such cost overruns are referred to as *complexity cost overruns*, and the uncertainties and possible negative effects are called *complexity cost overrun risks*.

Thus, mega infrastructure constructions can be defined by the following:

$$\text{Cost overrun} = \text{regular cost overrun} + \text{complexity cost overrun}$$

$$\text{Cost overrun risk} = \text{regular cost overrun risk} + \text{complexity cost overrun risk}$$

Not an abstract theoretical concept, complexity cost overrun has different forms, and accordingly, the risks are of different physical forms and require different types of management.

1. Overrun risk due to a complex construction environment

The natural environment for mega infrastructure constructions is, generally, complex and changeable. For example, hydro-geological conditions and weather are neither constant nor are they the same throughout the construction site. In fact, they may change within a short period of time. Even though necessary explorations are conducted during the evaluation phase, they involve only samples. Dramatic, sudden changes are possible and may occur in places at the site from which no samples were obtained, and there is no way for these changes to be known in advance. Therefore, if evaluators consider possible scenarios only on the whole, the costs they estimate based on the sample explorations are likely to be much lower than the final real costs, and the enormous overrun is incurred specifically, as a result of such complex conditions.

Furthermore key construction activities in mega infrastructure constructions often require an extremely strict outside environment that includes a proper window of time during which weather, hydrogeology, ocean currents, etc. are favorable. However, the dynamic changes in these complex factors suggest that such a window is rare or that the expected windows disappear quickly. This means that construction plans must be altered many times, which leads to increases in the costs of materials, labor, and equipment, and because these increases cannot be accurately estimated and listed in the budget, the ultimate result is a cost overrun.

Consider the Hong Kong-Zhuhai-Macao Bridge as an example. During one of the construction processes, the large marine tunnel tube had been moved to the construction site on the ocean surface by way of flotation transportation. It then had to be moved back because of a sudden change in the environment, thus making it impossible to continue with the construction. This to-and-fro transportation cost several million RMB, a cost that was outside the prediction.

2. Overrun risk due to deep uncertainty

A typical feature of mega infrastructure constructions' complexity, deep uncertainty, has many forms. Herein, however, only the deep uncertainty regarding the social and economic aspects of mega infrastructure constructions are considered. A country's political and social stability, economic development, financial safety, social credit, and monetary policies have tremendous influence on investments in mega infrastructure constructions, including the goals that the investment will control, the cost estimation, and the people and physical objects that must be moved due to the construction as well as how the people and objects will be resettled, moved, and compensated. Moreover, these factors themselves influence one another and result in a higher level of uncertainty and a huge increase in real costs. Thus, the result is cost overrun.

3. Overrun risk due to the system's emergence and evolution

System evolution and emergence, one of the important dimensions of mega infrastructure construction complexity, refers to the overall behavioral evolution of both individual systems, namely, nature, society, and economy, and the complex systems that consist of construction, physics, and people. Special attention is focused on the fact that the profound influence of mega infrastructure constructions, especially their large scale, is gradually released throughout the entire construction process. For example, construction may involve migration, rising land prices, environmental damage, and other hazardous changes, which means expensive contingency plans and remedies, in other words, substantial amounts of money. These changes, however, occur as the system within the construction project evolves. Thus, it is impossible for project subjects to make predictions at the beginning of the construction, let alone include the related costs.

4. Overrun risk due to project subjects' conflicting interests

Even more complex than systems such as physics and nature is human's adaptive behaviors. These are complex mainly because humans seek interests either through competition or exploitation. Accordingly, there are three types of interests-seeking behaviors:

(i) Conflicting outlooks on value may turn into cost increases. To explain this, a case study is presented. In a large bridge construction project, two completed piers were broken by a falling bridge girder erection machine. The construction contractor agreed to bear the emergency repair cost of 20 million RMB. However, this event also meant a 10-month delay, thus extending the original completion date. The owner, however, prioritizing an on-time completed project date due to political reasons, demanded a faster repair and allowed the purchase of a new erection machine. The owner added 0.2 billion RMB to the original budget to guarantee the original completion date. This is a case in which cost overrun occurs due to conflicting interests among different project subjects.

(ii) Another frequent and major driving force involves construction plan changes. During construction, contractors must alter the original contract, including the original construction plans, for various reasons. This is allowable, and there are clauses specifically regulating what alterations are acceptable. Normally, contracts permit necessary and reasonable alterations that arise from major forces. Contractors, however, may also propose alterations that are unimportant or even unnecessary with the intent to gain increased interest. Because mega infrastructure constructions often involve highly technical knowledge, contractors often take the upper hand because they possess more information. Accordingly, due to this information asymmetry, contractors may take advantage of reasonable alteration requests and ask for more than is necessary. In a word, alterations, originally rational and legal, may be exploited by contractors to obtain additional profits, also known as opportunism, an action that leads to increased costs.

(iii) Even worse, if contractors, supervisors, and/or other parties work together to seek illegal profits, also known as co-plotting, the overrun issue becomes even more complicated.

Though profit-seeking behaviors that involve twisting alterations are not uncommon in general constructions, mega infrastructure constructions involve more complicated networks of subjects' conflicting interests, more specialized construction plans, and, thus, increased asymmetrical information possession and larger amounts of money incurred by alterations. This makes it easier for behaviors such as opportunism and co-plotting to occur under the name of construction alterations, while the parties involved are actually seeking extra profits that lead to increases in costs.

5. Cost overrun due to construction innovation

Mega infrastructure construction projects require, in most cases, wide ranges of innovative technology. Technological innovation, as a complex system, entails an independent platform and an independent management system. The core of a technological innovation in mega infrastructure constructions is a technology breakthrough, which may go through three stages, namely, construction requirements, science and research management, and technology realization, a process similar to an upward spiral because of the interactions between innovation and practice. During the process, a deeper understanding of the natural environment and project technology is gained, and a gradually formed agreement among subjects is create. To achieve this, subjects must constantly compare, iterate, and converge, and during this process, they face uncertainty, repetition, and errors. The real situation varies with the complexity of the innovation in question and the managing ability of the platform, an ability that requires gradual improvement that is derived from the efforts of the subjects. This is primarily because technological innovation is a type of highly uncertain intellectual and creative activity whereby the cost of the whole innovation process is often much more than people think it would be. Moreover, as proven, people regard complex and highly complex innovative activities with a simple and certain thinking when they estimate the costs. Therefore, many of the innovation costs that occur later are either underestimated or ignored.

In addition, technological innovation in mega infrastructure construction is construction requirement-oriented, suggesting that there should be a technological threshold breakthrough, i.e., a breakthrough that is steady. This being said, in the interaction between innovation and practice, prudent and vigorous experiments and trial runs are necessary. For some of the experiments, it is not enough for them to be performed only in a laboratory setting; rather, on-site trials are essential. However, all of these require enormous amounts of money. This also contributes to cost overrun.

In summary, from the five subcategories of the complexity of mega infrastructure constructions, it is evident that complexity is, indeed, the main cause for mega infrastructure construction cost overrun. Furthermore, this type of cost overrun is fundamentally different from regular cost overruns. For example, the former occurs mainly because of nonstructural and highly uncertain situations that cannot be decomposed and then regrouped and those emerge and evolve as a systematic whole.

As a result, the following conclusions with respect to mega infrastructure construction cost overrun are proposed:

1. Mega infrastructure construction cost overrun (risk) consists of regular cost overrun (risk) and complexity cost overrun (risk).
2. Regular cost overrun (risk) and complexity cost overrun (risk) are fundamentally different. The former is the result of the difference between the costs estimated based on virtual project thinking and real project thinking in the sense of general systems, whereas the latter is the result of the complexity of mega infrastructure construction.
3. Complexity is the major contributor to mega infrastructure construction cost overrun. In this sense, complexity cost overrun, similar to a normal accident, is normal and accidental. Thus, it is not appropriate to blame this on the incompe-

tence or positive bias of the subject nor would it be proper to analyze the phenomenon by listing the items that caused the cost overrun because this reflection stops at an emotional or superficial level and lacks theoretical depth.

4. The complexity cost overrun phenomenon, which often occurs in reality, requires us to approach, analyze, and manage the problem by applying complexity thinking:

   (i) A principle based on the subjects' iterative behavior. In the first iteration, subjects must understand how to manage complexity, improve their ability to manage complexity, and learn to recognize and control complexity cost overrun.
   (ii) In the second iteration, a structure comprised of groups of subjects who are responsible for cost estimation and its process should be scientifically designed.
   (iii) In the third iteration, the compare and iterate process of non-consensus—consensus—non-consensus during the cost estimation was conducted to reduce errors and approach the final real cost. This substantiates that the solution to mega infrastructure construction cost overrun can only be produced through this iteration process.

5. Mega infrastructure construction cost overrun risk is unique among the risk types in the mega infrastructure construction's risk system. Accordingly, its uniqueness should be understood from the following two features. It is unique because of the complexity shared by mega infrastructure constructions and because of the uniqueness of the specific construction projects. Thus, common statistical methods, such as sampling or analyzing the overrun phenomenon by locating items that lead to cost overruns should not be used. Rather, the overrun problem should be addressed using the normal accident thinking.

It is emphasized that the focus is not to list specific reasons behind mega infrastructure construction and analyze them one-by-one, but rather the goal is to build a thinking mode for mega infrastructure construction cost overrun and overrun risk, especially to establish an understanding that based on the complexity thinking principle of the mega infrastructure construction management theory, mega infrastructure construction cost overrun is normal and accidental. Only by so doing can the impulse to find the reasons for cost overruns for each and every mega infrastructure construction be eradicated and a new method to understand and manage the problem be identified. This effort is both theoretically and practically beneficial because it enhances our understanding of the mega infrastructure construction cost overrun phenomenon and improves our ability to analyze and control cost overruns of this type.

Accordingly, it is fair to say that points 1 to 5, especially the last two, define, to some extent, the basic thinking and behavioral principle for understanding, analyzing, and coping with mega infrastructure construction cost overrun risks.

7.6.3 The Risk of On-Site Complexity in Mega Infrastructure Construction

The risk of on-site complexity to mega infrastructure construction introduced in this book refers to a type of risk that exhibits two basic characteristics:

1. This type of risk occurs at the construction site of mega infrastructure construction and is the result of the direct on-site complexity or the risk potentiality shaped by other preliminary management activities accumulated at the site.
2. This type of risk adequately reflects the disposition of risks, that is, the occurrence of the uncertainty of disaster. For example, current science and technology have made it possible to precisely forecast the intensity and path of typhoons. Even if the typhoon sweeps across the construction site, the uncertainty of people's cognition of its path is slim. Thus, typhoon is a disaster rather than a risk to the construction site; however, that is not the case for an earthquake, as an earthquake cannot be accurately forecast accurately, and thus it is an uncertain disaster (risk) to the construction site.

7.6.3.1 The Complexity Risk of Construction Environment

During the preliminary demonstration, detailed investigations and explorations of the construction environment have been conducted, especially with respect to the natural environment, i.e., the geology, hydrology, and meteorology of the location of the main construction. After all, the mega infrastructure construction is of such large scale that the investigations and exploration can only be conducted through the sampling of a certain coarse granularity, and thus, only the sampling information represents the overall information of the environment. Accordingly, the information between sampling points is deficient. If there is no discontinuity between the points, the risk of a sudden change to the construction environment may not appear, or there may be potential risks. In addition, by virtue of the complexity of the construction itself, the subject of the construction will find it difficult to fully clarify what information is complete, and the subject may even be unaware of what information he has failed to obtain. The subject of mega infrastructure construction is usually committed to on-site operations even though the information he possesses may be incomplete or severely deficient, a situation that is in sharp contrast to the actual complexity of the construction environment. This is a contrast between the complexity of the environment and the subject's incomplete awareness of the site, and as such, this becomes the main cause of a potential risk to the construction site.

For instance, the method of freezing rows of piles was adopted for the foundation of the south gravity anchor of China's Runyang Yangtze River Bridge. The foundation is 70.5 m long and 52.5 m wide, and the excavated foundation pits are 29 m deep, on average, thus reaching the surface of the bedrock. In fact, the freezing method drew on the methods employed in coal mining, wherein the freezing scope has a diameter of approximately 6–8 m. The world has never seen such a deep and lasting freeze as that which has been applied to the foundation of the south gravity anchor that covers an area of approximately 4000 m^2, a situation that presents a high risk to the construction site. Just as expected, problems occurred when the pits were excavated to a depth of 10 m. For example, some parts of the frozen walls failed to effectively stop water, and the shaft force of the internal brace increased at too high of a rate. Even worse, however, the anchor is located less than 100 m from the Yangtze River, which is connected by the underground water. These situations indicate that if the construction were conducted, there would be a high risk of water seepage and bursting, which would seriously endanger the safety of the construction of the entire foundation of the anchor. For this reason, experts were immediately organized to research the feasibility of the construction and examine the construction site. The experts contended that the primary causes of these problems are the unevenness of the stratum where the south anchor is located, the influence of the flowing underground water, which causes the frozen soil to be uneven, and the contractors' lack of awareness of and precautions against the risks arising from the complexity of the environment at the work site. As suggested by experts, certain precautions were taken immediately, such as partially strengthening the frozen area using liquid nitrogen and adding pressure relief grooves to the outer foundation pits. Moreover, based on the monitoring data acquired during excavation, a dynamic design was devised that called for adding to the structure of the internal support and timely controlling risks posed by the construction of the foundation of the south anchor.

7.6.3.2 The Complexity Risk of Construction Technologies

The complexity and peculiarity of any mega infrastructure construction manifests as a unique technological innovation and as an integration at the level of technology with respect to the construction site. In other words, any site of mega infrastructure construction cannot be an exact replica of another established construction technology. In this way, technological innovation and application form a new complex system of technology at the construction site of the mega infrastructure construction.

The complex system of technology at the construction site of the mega infrastructure construction incorporates technological selection, innovation, management, and application, each of which falls into several subsystems, thus forming a complex technological network at the construction site. This network not only has various forms of complexities regarding the relevance structure and technology transfer, but it also must coordinate the technological selection, control, management, and evaluation with quality, schedules, costs, and safety at the site of the mega infrastructure construction. In particular, the norms and standards of the technology of mega infrastructure construction must define the technological parameters through relevant experiments. However, as the experiments tend to be insufficient, they actually pose risks to the reliability and maturity of the technology. The real evaluation of technological innovation, in fact, cannot be conducted until the on-site construction of the mega infrastructure construction is completed. This means that new technology can only be applied on site through experiments and exploration, the process of which is an inevitable risk.

Furthermore, the on-site creation of mega infrastructure construction has transformed technological risk into an on-site normality. This is because what the mega infrastructure construction creates on site is not a standardized product made in bulk by companies on a production line but rather a distinctive single item of construction substantiality. Though each can be attributed to established plans, there exist risks in devising these plans.

Because it is impossible to entirely avoid on-site technological risk, effective methods should be developed to conduct on-site technological management and application to reduce such risk.

China's Hong Kong-Zhuhai-Macao Bridge is a typical example of mega infrastructure construction from which we can gain a profound understanding of how on-site technological complexity and risk occur and how the builders of the construction employ technological integration and innovation to reduce technological risk and accomplish the on-site construction tasks.

The main construction of the Hong Kong-Zhuhai-Macao Bridge is a 6.8-km-long submarine tunnel in the middle that is connected by immersed tubes. Each section of the tube is 180 m long and weighs 80,000 tons, similar to the weight of a large concrete building. During construction, tubes were prefabricated and then transported to seas under construction, installed in the carefully prepared foundation trench under the sea, and carefully and accurately joined together one-by-one. In total, 33 sections of tubes were joined one after another under the sea to form an integral submarine tunnel.

The submarine tunnel enjoys a service life of at least 120 years, and its construction site is in the South China Sea, which features complicated undersea conditions and terrible meteorological conditions and, as well, is subject to typhoons. Regarding this type of tunnel construction, there are no technological precedents from which to either at home or abroad. At present, there are more than 100 immersed tubes around the world, among which only a few are 40 m under water and even fewer extend over two kilometers long. The trench for this tunnel is 30 m under water and stretches over 3 km in length, statistics that are unprecedented in the world.

In July 2014, the installation of the E11 section of the tunnel tubes began at the construction site. The 80,000 ton section of tubes would be transported by floating them in the sea and installed precisely at the designated location 40 m beneath the surface of the sea. Moreover, a window of time featuring calm water and smooth sea currents is specified according to the complicated conditions of the weather, waves and sea currents.

First, the installation of the sections of immersed tubes required that the weather forecast define the accurate wind speed as meters per second. In turn, the data obtained from the meteorological satellite and the on-site observation instruments must be inputted into the super computer in Beijing, so forecasts can be made, and the data can be compared and contrasted with data from the installation site to optimize the forecast model and constantly verify its reliability. By so doing, the optimal period for transporting is tubes by water and installing them can be defined. This requirement is somewhat similar to the launching of a satellite. Finally, after more than 3 months of data analyses, the window of time for the immersion and installation of the tubes was determined to be from July 20 to 22.

The immersed tube tunnel of the Hong Kong-Zhuhai-Macao Bridge is the largest deeply buried immersed tube tunnel in the world. It is more than 10 m under water and has an excavated trench depth of over 30 meters at the seabed in which the immersed tubes are buried.

When the E10 section of the tunnel was being installed at the site, it was found through analysis that the water 40 m below sea level flowed at a rate much greater than the water 10 m below sea level, indicating that the sea currents in the trench did not accord with the general rule. However, there had been no research conducted on the technical principles of the deep-water foundation trench. Two forecasting systems were thus set up, one to forecast the large-area sea currents at the construction site and the other to forecast the sea currents a few hundred square meters within range of the installation of the immersed tubes. The computer analysis could calculate trillions of times within 1 s, fully showing the multi-scale management principle of mega infrastructure construction.

Among the calculations necessary was the accurate forecast for a small area. This proved to be a great technical difficulty because the immersed tubes had to avoid, based on the changes of the on-site sea currents, the large flows from both above and below. Thus, only two sections of the tube could be joined together when the deep water flowed at its minimum rate, which meant that both a large window of time and a small window of time were necessary.

Nonetheless, even with the relatively complete information regarding the sea currents, there was no technical scheme to control the process of sinking 80,000 ton tubes 40 m deep in sea currents from the sea surface to the seabed, which proved to be a major risk for tube installation technology.

The immersed tubes were controlled by a cable system while being installed. With the action of the sea currents, the immersed tubes would oscillate when sinking slowly. Thus, it was necessary to monitor, in real-time, the movement of the tubes as the sank in the water as well as the velocity and acceleration and the vertical and horizontal oscillation frequency and amplitude, all constituting data that needed to be precise.

Due to the large volume, the immersed tubes oscillated within a narrow range and vibrated slowly, a behavior known as low-frequency phugoid. For example, one oscillation might take over 100 s and cover a distance of only 10 cm, though it was extremely difficult to accurate measurements. Accordingly, correspondingly advanced technology, equipment, and methods were necessary for this task.

Hence, the construction unit developed equipment with high sensitivity, designed specialized methods and technical schemes, and set up a real-time motion monitoring system specifically devised for the on-site installation of the immersed tubes. The simulation results revealed that this system for monitoring minor motions of the tubes was highly sensitive and could accurately record data.

In the prescribed window of time, on July 21, 2014, the E11 section sank slowly toward the seabed. The measured horizontal oscillation amplitude was within 1 mm, and the vertical was within 2 cm, thus ultimately achieving the accurate butt-joint of the E11 section.

The process of employing the new technology describes the causes and mechanisms of the complexity risk of the on-site construction environment as well as the risk arising from the process of applying new technology. Furthermore, it reflects how the construction builders devised targeted and specific schemes and methods to manage on-site risks according to their types.

This case indicates that the risk analysis and control over the construction site of a mega infrastructure construction cannot be focused on the concept of general risk analysis, classified descriptions or overall evaluations as this type of superficial risk cognition and management cannot analyze the on-site risk of mega infrastructure construction or manage practical problems. In particular, the distinctiveness of the connotation of on-site risk management of mega infrastructure construction determines that it is inappropriate to employ the method of risk statistics and analysis because the on-site technical risks and risk control schemes of any mega infrastructure construction are, in a certain sense, unique and distinctive.

7.6.3.3 The On-Site Risk of a Normal Accident

1. Overview of a Normal Accident

In March 1979, due to the water loss dissolution of the reactor core and the release of radioactive material, a severe accident occurred in reactor number 2 of the Three Mile Island Pressurized Water Reactor Nuclear Generating Station in Harrisburg, Pennsylvania, USA. After the accident, approximately 200,000 residents in the vicinity had to evacuate the area. The president of the USA paid a special visit to the scene of the accident and organized experts to investigate the accident. Led by Perrow, a famous security expert, the investigation concluded that no one should be blamed for the accident, and if anyone or anything should be held accountable, it was the complexity of the nuclear generating station. On this basis, normal accident theory was proposed by Perrow in 1988 (Grimes 1985; Perrow 1981, 1994, 1999). The theory is of immense enlightening significance as it allows for the recognition and control of on-site risks at mega infrastructure constructions. The core idea of the theory is introduced by integrating it with the on-site complexity of mega infrastructure construction.

The site of mega infrastructure construction is a complex system characterized by close relevance between and among elements. Thus, a fault in any one part of an element may be passed on to other elements, thus causing new faults because of the close relevance. This process may be extremely rapid in the hard system of construction, making it impossible to guard against. Any system with such features is referred to as a *strong relevance system*. A strong relevance system is more complex with respect to system behaviors and features. For instance, the change of relevance between partial elements inside a system causes a relevance change between other elements. In addition, as the system can easily upgrade a fault from a micro level to a macro level, the strong relevance system often transforms minor and partial faults into overall risks that result in substantial losses. In this context, it is normal for the system to experience a risk because the underlying cause of the risk is system complexity, that is, the strong relevance between and among system elements causes element faults to be passed on and thus transformed into a system-level accident. It is further that the transformation tends to proceed on an unpredictable path and in an unexpected way, thus there is deep uncertainty that manifests itself as risky. Before this type of risk is formed or when it appears, people tend to not understand its cause and formation mechanism. Moreover, the irreversibility of risk means the tendency cannot be stopped and the original state of the system elements cannot be restored, thus worsening the situation either because of acting with confusion or adopting the normal operation.

The above cognition is of crucial importance for examining, understanding, and analyzing the cause and transformation of the on-site risk of mega infrastructure construction incurred by strong relevance. In particular, according to the normal accident theory, because the control mode and method for this type of risk is no longer at the element level, but at the system level, the risk control system should be designed and developed considering the importance of strong relevance thinking.

2. The Risk Control over an On-Site Normal Accident

The risk formation mechanism and risk control concept of an on-site normal accident in mega infrastructure construction can be analyzed from the perspective of the normal accident theory.

At the site of mega infrastructure construction, all types of personnel, equipment, and raw materials are gradually incorporated into a complex system by a complex process of specifications and management procedures. This system is not simply a physical system of things but a complex system of people and things; within this system of things, there exists not only the principle of machinery but the principle of hydraulics and the principle of civil engineering as well as a complex system of people. Thus, the risk to the system hinges on the quality of the equipment and materials, on the psychological state and behavior of the personnel, and on the management procedures and standards. As a consequence, the substantial complexity that is manifested at the site of the mega infrastructure construction is grounded on strong relevance and is, in general, far greater than the insubstantial complexity estimated and predicted by the construction design. There are several reasons for these phenomena:

(i) The horizontal relevance between and among elements at the site of the construction is greatly enhanced.
(ii) The causality is not direct, and the complexity reduces the predictability of a number of issues at the building site of the construction.

(iii) The influence of the weak force generated by some factor at the site may spread and be amplified from partial to overall and from slightly traumatic to disastrous. That is, the strong dependence of an on-site accident at a construction location on the path may transform minor differences in the initial state and early conditions of the construction into a major accident at a later point.

(iv) A construction accident is characterized by unpredictable abruptness. Thus, because the accident often occurs in irregular ways, and according to unusual procedures people can neither predict it or recognize it when it occurs.

(v) In the face of an accident, normal operations may increase the severity of the accident rather than decrease it.

(vi) People will increase relevance to reinforce the system and strengthen its security. However, given that everything has two sides, when the relevance of the system is increased, the complexity is also increased, thus raising the possibility of accidents.

These characteristics suggest that at a mega infrastructure construction site, even if the quality of every facility is superior, even if every link in the process is as perfect as possible, even if every technician is as skilled as possible, and even if every management procedure is as strict and precise as possible, just as Murphy's Law states, the potential for error and the possibility of an accident always exists. In particular, for any minor accident that involves the security of the construction, regardless of whether it involves equipment, personnel, management, or the environment or a combination of these factors, if some fault occurs, even a minor one, the strong relevance of the construction is likely to cause the amplification of the fault or an interaction between faults and consequently cause the occurrence of systematic accidents. These, however, are far beyond the former experiences of on-site personnel and the expectations of construction design personnel, a situation that ultimately causes originally normal operations to trigger serious accidents.

The above analysis is of considerable guiding significance for defining the risk control concept of the strong on-site relevance of mega infrastructure construction.

Undoubtedly, materials and equipment of superior quality, personnel with excellent qualities, and in-place perfect management procedures are extremely important for preventing risks at the construction sites. However, greater attention should be given to the impact of complexity on on-site construction risks, and by all means, the passive risk control mode characterized by judging a case as it stands should be avoided, and an active risk prevention system should be established. The system should start from the set of all factors related to the construction accident and emphasize that risk prevention is of the utmost importance.

Primarily through the synergies of on-site risk management and the organization system, the risk education and training system, the construction risk responsibility system, the risk prevention and control system, and the risk emergency plan system, the risk control concept of risk prevention is of the utmost importance can observe, measure and evaluate the factors of on-site risks, constrain them within the allowable range, and monitor them by standardized and procedural means to prevent risks at the construction site.

The risk control modes, according to the on-site situations of the construction, belong to one of three:

(i) The centralized risk control mode should be adopted when related links of the construction site present strong relevance to each other but low mutual influence.
(ii) The decentralized and integrated risk control mode should be adopted when related links of the construction site present weak relevance to each other but high mutual influence.
(iii) The centralized and decentralized risk control mode should be adopted when related links of the construction site present strong relevance to each other and high mutual influence.

In addition, once an accident occurs at the construction site, the focus should not be entirely on identifying the responsible person. The reason for this is that the person responsible for the on-site risk control of the mega infrastructure construction may not be a person, but rather, the complexity of the system may be responsible. This requires identifying the cause of the risk as well as the mechanism of the major accident caused by the risk. This mechanism is, more often than not, the person or system responsible for the accident. Such an incident serves as an extremely valuable case from which to learn.

The optimal operating method for on-site risk control, once the accident investigation have been completed, is the timely modifications and improvements in the risk control standards and methods and the transformation of each security lesson into an asset. Furthermore, during the risk control process, regarding suspended and prevented accidents, the emphasis should be on converting relevant experiences into valuable resources that continue to improve and perfect the on-site risk control methods. This is because the on-site risk control of mega infrastructure construction, in accordance with the concept of complexity management, is a process of constant improvement and perfection aimed to minimize risks.

3. A Typical Case

Early in 2006, an accident occurred at the construction site of the north approach to the China's Su Tong Yangtze River Highway Bridge when the bracket of the left motion module for the 50 m span box girder unexpectedly fell. The direct cause of the accident is attributed to the fracturing of a fastening bracket of the motion module which then caused the upper part of the bracket to separate from its propulsion unit. Because the propulsion unit of the bracket was linked to chain hoists, when the bracket fell, the inner propulsion unit fell as well. It then crashed onto the bracket and damaged the steel plate connected to the oil cylinder of the horizontal propulsion unit, resulting in the loss of property and in casualties. The structure of the device is presented in Fig. 7.21.

The fracture was scanned and analyzed using an electron microscope and then examined by microstructure after the accident. It was found that to prevent the shaft from rotating with the fastenings under it during operation, the initial equipment design unit incorporated specifically designed welding positions and seams in the

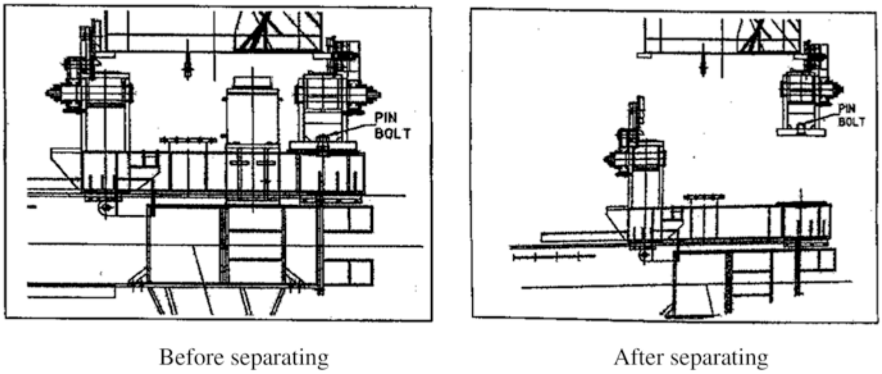

Fig. 7.21 Structure diagram

drawings and welded the shaft to the lower working pieces. However, owing to blemishes in the welding technique, the welding joint did not meet the hardness value specification, and thus, the accident occurred.

The sequence of events regarding this accident are as follows: the equipment was designed to prevent rotating—the parts were welded according to design specifications—the excessive hardness value in the heat-affected zone of the welding joint was insufficient due to technique blemishes—a minor fracture occurred at the site of the joint where the hardness value was insufficient—the fracture expanded—the bracket broke off as a result of the fracture—the inner propulsion unit fell and crashed onto the bracket—the oil cylinder on the horizontal propulsion unit ejected.

The carelessness in the design of the equipment and the manufacturing technique eventually led to a serious accident. In the life cycle of the moving support system, all of the abovementioned links were normal, and all operations were regular. However, an occasional, minor mishap occurred and was gradually amplified by the strong system of relevance, causing the occasional mishaps to suddenly transform into an accident. It is evident that the mechanism of the accident is completely consistent with the sixth point of the new thinking summarized earlier in this section, that is, people will increase relevance to reinforce the system and strengthen its security. However, as everything has two sides, when the relevance of the system increases, the complexity also increases, thus raising the possibility of an accident. Accordingly, this accident is a typical example of the normal accident theory.

After the accident at the Su Tong Yangtze River Highway Bridge, an emergency plan for risk contingencies was urgently launched, the causes were identified seriously, and the security monitoring system was immediately extended to overseas equipment manufacturer to prevent any normal mishap with low probability from causing serious accidents.

Based on the theoretical research and the practice of on-site risk control, the basic principles for controlling risks at the construction site are further summarized.

(i) To reduce the occurrence probability of on-site risk, the risk assessment during the planning period of the construction is extremely significant. In the planning stage of the construction, normal accident theory should be fully applied, the conventional risks should be controlled, and the construction complexity degree should be analyzed from six perspectives, namely, construction design, construction equipment, operation procedures of construction, construction operators, construction equipment and materials supply, and the outside environmental conditions. It is feasible to analyze similar constructions that are currently in operation from the same perspective and obtain the history of their risk events. In this way, the complexity degrees of similar constructions can be compared, the relative position of the designed construction complexity degree can be located, and further speculation regarding risk probabilities can be conducted. If the probability is high, other alternative technological processes may be adopted to reduce the complexity degree of the entire construction and the security at the site can be enhanced.

(ii) During the construction stage, in addition to controlling the construction risks using traditional methods, normal accident theory should also be considered to raise risk awareness. Herein, the theory is applied to the risk control mode during the stage of construction.

First, to reduce the normal accident risk related to construction, a reasonable risk control system must be established prior to which a predictive assessment of the construction complexity degree should be conducted during the planning stage. Following this same method, the management personnel can assess the construction complexity degree, establish a scientific framework for the risk control system based on the assessment results, and reduce the accident risk at the construction site.

Second, slightly different from the assessment in the planning stage is that, in the construction phase, the management personnel must assess the degree of construction complexity degree from two perspectives, i.e., the closeness between links and the mutual influence on departments. With this assessment framework, three risk control modes based on normal accident theory can be employed based on the specific circumstances, i.e., the centralized risk control mode, the decentralized risk control mode, and the centralized and decentralized integrated risk control mode.

(iii) In accordance with normal accident theory, some accidents in construction may not be the result of human fault. Thus, the primary concern for management personnel is to determine the real cause of the accident rather than the responsible person. Only by revealing the essential cause of the accident can control over the construction risk be strengthened.

To better employ normal accident theory, several issues of importance must be considered while establishing the on-site risk control framework according to the guiding ideology of normal accident theory.

First, it is necessary to integrate the present on-site risk control system with normal accident theory to develop a more perfect and effective risk control system at the construction site.

Second, emphasis should be placed on the prevention of accidents. According to normal accident theory, an accident that arises from complexity at a mega infrastructure construction site is inevitable, but the probability of its occurrence can be reduced. However, there is little research regarding how to develop a risk prevention mechanism grounded on normal accident theory to precisely predict the probability of a normal accident. For the moment, the management personnel of the construction can only make predictions based on their experiences in risk control. It is believed that improvements will be achieved in this regard as future research on normal accident theory of construction is conducted.

Finally, stress should be a factor when considering improving risk control. As modernized construction continues to be enhanced at construction sites, significant environmental changes will occur at these sites, and as a result, decomposing the on-site complexity degree is, in effect, a process of constantly improving risk control.

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Main Theories in Part 3

This section, as the core of the book, is a practical exploration of and an attempt to establish a fundamental theoretical system for mega infrastructure construction management that is consistent with the general paradigm of establishing a theory.

First, by compacting and abstracting the essential properties of every key link and every important element in the practical activities of mega infrastructure construction management, basic concepts of the theoretical system for mega infrastructure construction management have been developed. These concepts serve as the basic unit for people to perceive management activities, and they embody the identity, universality, and regularity of the properties of management activities and issues.

Accordingly, nine concepts related to mega infrastructure construction management activities are developed, namely, the mega infrastructure construction-and-environment complex system, management complexity, deep uncertainty, scenario analysis, management subject and core subject, management platform, multi-scaling, adaptation, and function spectrum. Each of these concepts has a clear and specific context for managing practical activities that includes the phenomenon, scenario, and subject behavior, thus indicating that the nine basic concepts are from the practical activities and phenomena of mega infrastructure construction management. In this way, the basic concepts substantially abide by the thinking principle of mega infrastructure construction management theory. Furthermore, from these concepts, which cover management activities and issues of mega infrastructure construction in a holistic and comprehensive manner, a close, logical, and systematic association is formed.

The subject and the characteristic of complexity are the two most essential and common elements among the activities, phenomena, and issues of mega infrastructure construction management. Without the subject, there will be no construction management activities, and without complexity, there will be no management activities of mega infrastructure construction. Thus, with these two elements as the core of mega infrastructure construction, five basic principles are proposed, namely, complexity degradation, adaptive selection, multi-scale management, iterative generation, and hierarchical principal agent. These principles not only adequately

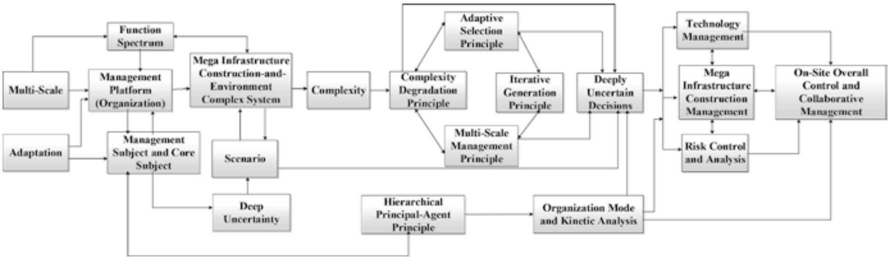

Fig. 1 Logical relations among basic concepts, principles, and scientific issues in the theoretical system of mega infrastructure construction management

maintain the properties of managing the complexity of mega infrastructure construction, but they also reveal the basic rules of causality, association, and logical relations between the subject's code of conduct and the operating principles and between the management phenomena and the activities of mega infrastructure construction management.

On this basis, the scientific issues from six fields that are inferred from fundamental principles according to core concepts reveal the profound connotation of basic complexity issues in the theory of mega infrastructure construction management. Among them, issues such as the kinetic mechanism of the management organization of mega infrastructure construction, deep uncertainty decisions, perceptions of the quality of decisions on basic scenario robustness, mega infrastructure construction finance, technology management, overall on-site control, collaborative management, and complexity-based construction risk analysis enrich the traditional knowledge about project management and abstract new and extensive scientific value and provide practical guidance from the essential property of mega infrastructure construction management, thus deepening people's understanding of the complexity of mega infrastructure construction management and enhancing their ability to control the practice of mega infrastructure construction management.

Moreover, the theoretical system of mega infrastructure construction management is described in detail, and the basic concepts, principles, and scientific issues of the system are also detailed. The logical relations and the systematicness and orderliness of the entire theoretical system are discussed, and a diagram of the system is presented in Fig. 1.

Part IV
Methodological System of Theoretical Research on Mega Infrastructure Construction

Section 4.1 defines system complexity as the thinking principle of the theory of mega infrastructure construction management and accordingly establishes the epistemology for theoretical studies in this field. That is, the essence of problems in the theory of mega infrastructure construction management has already been confined to the category of complex systems, regardless of the specific form of these problems.

The epistemology corresponds to the methodology in that the thinking principles in the research lead to corresponding research methods, namely, research methodology. Further, the method system of theoretical research of mega infrastructure construction can be developed in terms of the features of the methodology as well as the research problems.

As for the new theoretical system of mega infrastructure construction management, which has specific regularities, it is necessary for this theoretical system to have a complete design and an overall approach to solve problems, and it is necessary to develop a methodology and method system that specializes in mega infrastructure construction management.

Chapter 8
The Method System of Meta-Synthesis in the Study of Mega Infrastructure Construction Management

The principle of constructing research methodology and method systems in terms of the thinking principle of complexity in mega infrastructure construction management theory is critical to the development of the theory. Therefore, it is significant to understand how to select and innovate research methods when studying management problems in mega infrastructure construction.

8.1 Overview of Methodology

There should be appropriate and targeted methods for studying and solving theoretical problems of mega infrastructure construction management. First, it is necessary to determine the overall research methods or principles and establish the method systems according to the attribute of system complexity of the problems.

The methods and principles that match the system complexity are referred to as methodology. People generalize all types of methods in a certain field and develop general laws and principles for research methods, that is, the *methodology*.

Methodology refers to the ideas and principles that people are to understand, analyze, and solve problems of certain types by applying various methods and means (Ethridge 1995). However, problems cannot be solved merely with general ideas or principles. Rather, solving problems requires that specific methods be implemented under the guidance of methodological principles. Without a methodology, the methods may be created, selected, and applied in a way that is piecemeal, illogical, unrelated, inconsistent, and irregular. Without concrete methods, the methodology can only be confined in its generality, leaving no room for practical operation. This indicates that the methodology and the method are correlated, though they may well be at different levels.

It has been previously noted that mega infrastructure construction management involves many fields, such as natural sciences, social sciences, and human

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disciplines, and thus, there are various choices and combinations of research methods. Because management is a practical activity with its own rules, it is best to establish the methodology, that is, the normative methodological principle, before selecting, arranging, and creating concrete methods. The main purpose is to study how to construct a method system that intercrosses and incorporates different contents under the guidance of the principle of managerial thinking (Xu et al. 2008).

Thus, one of the major tasks in establishing the theoretical system of mega infrastructure construction management is to build the corresponding methodological system. Because the methodological issue concerns not only the researcher's academic pursuit but also the comprehensiveness of the theory, the methodological research is a process of continuous discovery, advancement, and improvement.

Yu Jingyuan, the famous Chinese system scientist, has conducted several studies on the methodology of mega infrastructure construction management and the organization and management of complex systems. His academic ideas and discussions are extracted from several papers and presented herein.

"In a relatively long period people benefit quite a lot from using the simple reduction method to solve management problems in managerial activities of general project. The essence of this method is to decompose a problem into parts that are simple, definite, detachable, reversible and reducible and then study them respectively in order to get an overall knowledge on the original problem through adding them together. The methodology in this method reflects that people mainly follow the approach from decomposing, to reducing and then to reuniting a problem so that the problem can be made clear. In this process the whole will be broken down into parts and the high level will be reduced to lower levels and then these parts and lower levels will be integrated after their nature have been disclosed. By doing this, the overall characteristic of the whole problem is disclosed" (Yu 2014).

"The reduction method teaches us to separate the research object into parts, on the supposition that we will understand the whole if we have understood its parts. If we do not know the parts clearly then the separation continues, thus ad infinitum until we have seen all of these through. In other words, this method make the research become more and more concise, which constitutes its major advantage. However, it is always the case that we cannot go from these concise parts back to the whole and answer by virtue of them the problem with high level and more integrity, which constitutes its major disadvantage. Therefore, only with the reduction method the whole job cannot be finished; it also require the knowledge about how to go from parts back to the whole" (Yu 2014).

The reduction method satisfies a great deal of our needs when solving management problems in general project management. However, as the complexity of mega infrastructure construction management increases, the shortage of this method gradually becomes increasingly more distinct. For example, it cannot solve a large number of complex systematic problems in mega infrastructure construction that are nonadditive and stratified (Fan 2008). The problems provided in the previous sections, such as the integrated system of mega infrastructure construction and environment, the subject collection, the function spectrum of mega infrastructure construction, and the horizontal and vertical relationship of mega infrastructure construction, are complex systematic problems that cannot be managed or controlled via the reduction method.

"At this moment, the importance of the methodology about the study of systems is recognized. *The system theory is the methodology about how to study holistic systems*. It starts from the notion that for the systematic problems it is incorrect to replace the knowledge of the system with the sum of the knowledge of the parts of the system by using the reduction method to reduce the systematic problem to parts. This notion is essentially practical and correct. However, it is usually difficult to find the method and the tool that directly study systems. Thus, despite its role in recognition plays with more and more significance, the system theory cannot be developed and applied successfully in practice and therefore appears as the thinking principle followed by people in learning and handling complex problems. For instance, the general system theory, though having been put forward in 1940s, is actually the holistic method, which stress on studying problem from the view of system. However, the specific methods that support holistic method are far from being established. Therefore it remains to be the discussion of from system to system and from qualification to qualification, but no problem is able to be solved from it" (Yu 2014).

8.2 The Method System of Meta-Synthesis in Mega Infrastructure Construction Management

8.2.1 The Methodology of Complex Systematic Problems

Over the past several decades, scholars from various countries have conducted studies on system theory and related methods in different domains and on various issues, and they have achieved many results. In China, in the1970s, the famous control and system engineering scientist, Qian Xuesen, creatively integrated the system theory with the reduction theory after decades of practice in major aerospace engineering. He proposed the methodology for knowing, analyzing, and managing in the organization into the management of mega infrastructure construction. The basic principle of this methodology is that in dealing with management problems of mega infrastructure construction, the problem must first be separated into its parts from a systematic perspective of the problem and then the parts must be reintegrated to form the whole before finally solving the problem.

"In the early 1980s Qian Xuesen put forward a kind of system theory that dialectically combines the holistic approach with the reduction method, set from which he developed the relevant methods. When applies these methods one should decompose the system in a whole and then based on the researches after the decomposition study the system again with these researches in order to make a holistic occurrence of the system and finally study and solve problems systematically" (Yu 2014).

"It is clear that the method of system theory absorbs merits of reduction method and holistic approach but makes up for their shortages. It goes beyond the reduction method and develops the holistic approach, which provides significant instruction for solving and researching the complex systematic problems in mega infrastructure construction management" (Yu 2014).

When the methods of system theory are applied to the practice of mega infrastructure construction management, it is necessary to establish an organization that is composed of management subjects who are familiar with the construction system and that is directed by experts who have a broad knowledge background (Dai and Cao 2002). The organization must design and provide a general management scheme; specifically, it must provide the systematic technical approach and methods according to the overall goal.

To study and manage the problems, the organization considers the various parts and problems of the managerial activities to be constituents of the whole system to which it belongs. Thus, the goals of the organization and the solutions to the problems are part of the entire system of construction. The organization should also design mega infrastructure construction managerial activities by considering such activities to be a system of interrelated parts. The goal and requirement of each part should conform to the overall goal of the management activity. In a word, the organization should consider the conflicts between different parts and problems as part of the general goal of mega infrastructure construction management.

"By virtue of methods mentioned above we need to make the overall analysis, demonstration, design coordination and plan for the systematic structure, environment and function of managerial activities of mega infrastructure construction. This process involves the usage of various instruments and methods from natural science, social science and human discipline so as to make qualitative and quantitative analysis for management problems, build system model and simulation for these problems and do the relevant experiments and assessments, in order to generate a satisfactory and reliable overall scheme which can serve as support for the decision department to support the scientific decision and for the construction department to make reference.

Though it is universally known that the object of managerial organization of mega infrastructure construction is the constructing activities, the practice of project management, however, is related profoundly to the integration and allocation of staffs, capital, goods, information and knowledge, and to the study about how to ensure with low cost, high quality and reliability, and to other decision and management issues such as institutional mechanism, development strategy, planning program and polices. All of these belong to the 'soft' system of management other than the construction, which is the 'hard' system. The two systems are intimately connected with each other and constitute a new system" (Yu 2014).

Apparently, the new system is much more complex than the hard system in that it represents the attribute of the construction as both a social system and a human system. If the hard system calls for the integration of the knowledge of natural science, then the new system demands the combination of the former with the knowledge of social science and human discipline (Wang and Cheng 2009). Managing this system, however, has transcended the general system of engineering and has become the aim of complex systematic construction.

Thus, it follows that *mega infrastructure construction management belongs to system theory management with respect to methodology*. The chief problem of system theory management is how to study and solve management problems from a systematic perspective. Therefore, assisted by system theory, it is essential to understand the complexity of the system and learn to manage it (Yu 2009).

To sum up, the principles and approaches of the management methods of system theory were developed by combining the system theory with the reduction methods due to the complexity of the management problems in mega infrastructure construction and the integrity of the management activities, which Qian Xuesen proposed in the meta-synthesis method (Yu 2001).

8.2.2 The Meta-Synthesis Method of Mega Infrastructure Construction Management

By the 1980s, Qian's thoughts regarding system theory had become much clearer. He posited that because it was necessary to study and solve problems generated in mega infrastructure construction at the macro level, it was necessary to resort to the knowledge from different fields and disciplines and to combine human power with the advantages afforded by computers. He also suggested the need for the wisdom and collaboration of experts from different domains and the need for scientific methods with respect to qualitative analyses, quantitative analyses, and experiments. Based on these contentions, he proposes the theory of meta-synthesis and advances the notion *to build a meta-synthesis method that combines the reduction method and the method of system theory* (Qian 1981, 1982, 1991; Qian et al. 1990).

This system, which is founded on mega infrastructure construction management and is proposed following Qian's long-term study, is a systematic method that integrates technologies and methods from various disciplines and fields and could be used to understand, analyze, and solve the complex management problems of the mega infrastructure construction system (Qian et al. 1990). Essentially, the complexity of these problems is derived from the subjects' inadequate knowledge and the deep uncertainties associated with the object and the environment. Thus, when applying the meta-synthesis system to manage these problems, several advantages can be realized.

1. The management subject can utilize all types of management resources and methods through synthesis to improve his ability to know, analyze, and manage complex management problems.
2. The management subject establishes a process that enables him to identify and analyze complex management problems. This, then, leads to the production of a final scheme for solving complex management problems based on a sequence of schemes whereby the schemes improve from relative disorder, inaccuracy, and chaos to the final scheme, which approaches perfection and accuracy with respect to solving complex management problems.

It is evident that the meta-synthesis method corresponds to the complex management problems in mega infrastructure construction with respect to the problems' features and the principles of and approaches to solutions. Furthermore, the meta-synthesis system is consistent with the basic principle of mega infrastructure construction management.

The significance of this system in solving complex management problems in mega infrastructure construction is multifaceted.

1. The management of mega infrastructure construction has relations with politics, the economy, society, technology and human disciplines. In other words, such broad and various fields that it is not realistic to expect that all problems can be solved with a single idea, from a single perspective, by one method and with only a few people. Rather, solving such varied and complex problems requires the combining of knowledges from multiple disciplines, the combining of governmental functions with the functions of the market and the experiences of the experts in scientific theory, and the combining of qualitative analysis with quantitative analysis and computer technology to highlight and exploit the overall dimensions of the new management competence by integrating them. This is the premise of the system of meta-synthesis (Li et al. 2009; Wang and Cheng 2009).
2. Managing a mega infrastructure construction requires the exploitation of the broad knowledge and vast experiences of relevant experts. It requires, by virtue of the mathematical methods, a precise quantitative analysis of the numerous relations among managing activities; it requires the use informative technology to simulate scenarios, and it requires the actual scenario to be combined with the qualitative analyses, quantitative analyses and simulation results, the perceptual knowledge to be combined with rational knowledge, and the practice to be combined with theory. The result of fulfilling these requirements is the possession of comprehensive, profound, and accurate knowledge regarding mega infrastructure construction management (Sheng and You 2007; Sheng et al. 2008).

More specifically, in the practice of mega infrastructure construction management, many types of models must be built according to the various relevant information and data. These models should be based on practice, experiments, and experiences and should be tested and verified with the aid of experts (Yu & Zhou, 2002). Therefore, the entire process sufficiently employs a combination of knowledge, skills, people, and ideas that lies between science and experience, perceptual knowledge and rational knowledge, and qualitative knowledge and quantitative knowledge. Furthermore, the process is elevated from experience to theory and from qualitative knowledge to quantitative knowledge, thus resulting in access to knowledge that is as precise as possible when seeking to solve complex problems.

3. The management of mega infrastructure construction requires the organization and management of large amounts of data and information that are the results of computers that have rapid information processing speed, enormous memory capacity, and strong reasoning ability (Newell and Simon 1976). Nonetheless, solving management problems also requires concrete thinking, creative thinking,

qualitative judgment, and the wisdom to manage complex problems, all of which cannot be completed without the advantage of people. Therefore, the two advantages, people and computers, should be closely combined in the field of management. In other words, men and computers should be combined to create a new complementary advantage and generate a greater capacity to solve complex problems (Yang and Du 1996). Given the computer's disadvantage to think concretely and creatively, man's experience, wisdom, and dominant functional abilities are required when applying the man-machine combination mode (Huang 2005).

4. In directing the management work, the meta-synthesis system has developed a management system that is capable of analyzing, judging, and solving complex management problems. This management system is composed of several parts.

    1. A recognition system that analyzes the complex management problem.
    2. A coordination system that operates and oversees the management activities.
    3. An executive system that provides comprehensive control at the work site (Xu et al. 2008).

5. The complexity problem must be analyzed systematically, whereas more general issues, such as the objectives and content analysis, the special analysis of structure and function, and the system optimization and scheme selection, must be directed by system theory. For instance, the decomposition of management goals must be based on the general objective of management, and the scheme appraisal must be conducted through synthesis. Hence, the analysis of a complex problem must be an iteration process of synthesizing-analyzing-integrating-decomposing (Sheng and You 2007).

Similarly, processes such as element clarification, rule making, and model selection must also adopt the mutual coupling method of analysis, synthesis, decomposition, and integration.

To sum up, the system of meta-synthesis involves the overall design being directed by the system theory to solving the complex problems in mega infrastructure construction management. Accordingly, the system does not aim to select specific methods to solve certain problems for aspecific project. The system of meta-synthesis ensures the establishment of scientific methodology under the guidance of system theory and also ensures the selection of appropriate methods that address the management problems and support the system theory.

In fact, various methods from various fields, including management fields, play important and effective roles when managing the complex problems of mega infrastructure construction. This indicates the importance of multiple disciplines to mega infrastructure construction. Because the problem of complexity has its own essential properties, there should be special targeted new research rules and methods. Without this, it is neither acceptable nor appropriate to claim that a complete theory system for mega infrastructure construction management has been established.

Under the direction of the meta-synthesis method system, when considering how to construct the new, specific, and effective methods for mega infrastructure construction, it is imperative to seize and refine the central, crucial, and most needed common tools and methods for solving management problems by combining the meta-synthesis system with the essence of management and to apply these tools to successfully solve problems.

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Chapter 9
Specialized Methods in the Research of Mega Infrastructure Construction Management

It has been previously emphasized that mega infrastructure construction management involves many fields, including politics, the economy, society, technology, and human disciplines, and that no management that masters the overall complexity of the management problems can emerge without the integration of the natural sciences, social sciences, and human disciplines. This fact suggests that different types of methods are demanded for solving management problems in mega infrastructure construction. Thus, the exploration and introduction of new methods directed by theoretical methodology of mega infrastructure construction management are required. Accordingly, four points must be emphasized:

1. Regarding the management problems of mega infrastructure construction, there is a group of problems concerned with engineering technology and natural laws that can be solved by quantitative methods that are widely used in other fields. However, people may also create and implement new quantitative methods in mega infrastructure construction management, but these methods are usually regarded as improvements of existing mature methods rather than new methods. In other words, in the theoretical research of mega infrastructure construction management, there are few completely new and unique quantitative systems. Therefore, there is no need to provide a list of these mature quantitative methods.
2. There are many qualitative methods in the theoretical field of mega infrastructure construction that are identical to those used in social science research. However, because the management problems of mega infrastructure construction have unique properties, there must be a class of new methods other than the ordinary quantitative methods that demonstrate this feature. Hence, the panoramic qualitative analysis is introduced.
3. In recent years, the information and computer technology field gains increasingly more weight in the research of mega infrastructure construction management. For example, technologies such as computer simulations and computational

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experiments provide new means for the managerial activities to reconstruct and discover scenarios. In particular, it provides new methods to characterize and describe the complex wholeness of management problems, which cannot be achieved using the traditional quantitative and qualitative methods. Therefore, scenario farming is selected as a new typical method to illustrate.

4. Models must be built that represent the entirety of the managerial activities in mega infrastructure construction. The models must be of various complexities, and they must conceptualize, to some degree, the active entity and refine the essential property of the active entity at a theoretical level. This is the process of mega infrastructure construction management modeling. Based on the integration of current advanced modeling thinking, especially that based on information technology, and on the reflection of the complex wholeness of mega infrastructure construction, the new method of federation modeling is introduced.

The abovementioned methods are named in this book according to the specialized methods in the research of mega infrastructure construction management.

9.1 Specialized Method 1: Panoramic Qualitative Analysis

One of the specialized methods, the panoramic qualitative analysis, is detailed in this section.

9.1.1 Overview

Quality, or essence, which is defined as an essential property, refers to the inherent characteristic that distinguishes one thing from another. The essence of mega infrastructure construction management, and, thus, the quality that discriminates it from other types of project management, is complexity or complex systematicness (Rhodes et al. 2010). Accordingly, the study of mega infrastructure construction management from the systematic perspective should focus on the complexity or complex systematicness of management problems and should resort to the methods of conceptualization and reasoning (Flyvbjerg et al. 2002). Furthermore, when the study is concerned with the managerial activities and problems in particular, it must be noted that the management will not only reflect the universal characteristic shared by all particular managements, but it will also indicate the individual characteristics of a particular construction.

A profound understanding of the nature of this particular construction cannot be gained without disclosing its specialty. To study the general quality of mega infrastructure construction management, the general qualities are derived from the generalization of many specialties of constructions. Therefore, conducting qualitative research should be considered a common and fundamental paradigm for particular managerial activities and problems related to the study of mega infrastructure construction management.

For instance, neither the decision confirmation, program design of a proposed construction, nor the decision generalization and reflection of a completed construction can be conducted only in a general sense, as these decisions are made under circumstances of deep uncertainties. Furthermore, the conceptualized research lacks value in both theoretical analysis and practical instruction. Therefore, what is needed are strict analysis of certain features, such as the decision program design and program robustness, based on the construction to identify the specialty of the decision-making activity of mega infrastructure construction (Brown et al. 2004; Leifler and Eriksson 2012). Thus, this process is intended to study the essence of mega infrastructure construction management.

9.1.2 The Method of Qualitative Analysis

It is known in management science that there are two basic research methods: the qualitative method and the quantitative method. The quantitative method uses numbers, mathematical symbols, and mathematical language to deduce the general law of management problems, i.e., using mathematical models to analyze quantitatively the essence of the research object and using calculus and theorems as proof. The qualitative method is widely recognized as all research methods that are not quantitative methods. As such, it concentrates on using verbal descriptions, expositions, and exploration to study management phenomena, events, and issues (Masera and Wilkens 2001).

The various qualitative methods vary significantly with respect to academic background, procedures, and means. Consequently, the qualitative method should be selected based on the characteristics and demands of the special problem.

In practice, when a qualitative method is selected, it does not imply that this method is perfect in every respect or that the method that was not selected is inadequate. More commonly, people often employ one method as the foundation and then combine it with merits of other methods or integrate many methods into one new and more effective method.

This principle in methodology emphasizes the innovation of qualitative methods and suggests that the innovations in methods could be explored by focusing on the essence of the management problems in mega infrastructure construction based on the qualitative method that already exists.

To explain the new qualitative method proposed in this book, it is necessary to begin with the qualitative research, which is the basic method of research in the study of social sciences.

Qualitative research studies research objects by virtue of researchers who directly address the research objects by collecting in-depth information under a natural setting. This method is the systematic research method whose application requires the profound and precise exploration of research objects through the interaction between the researchers of extant studies and the research objects conducting the current investigation. In this sense, it involves the generalization of information by virtue of which theories can be developed, and explanations for phenomena can be provided (Denzin and Lincoln 2005; Lin 2015; Major et al. 2013).

According to the academic research on this subject, this method consists of four characteristics:

1. A focus on natural scenarios. The qualitative research focuses on the direct treatment of the researcher toward the research objects being investigated under a natural and real scenario and on the face-to-face communications between researchers of existing studies and the research objects conducting the current investigation with respect to the problems that the investigative researcher encounters or addresses. This not only requires knowledge about the specific vivid real scenario, but it also requires knowing about the occurrence and development of the problem as well as the mutual influence and interrelation between the problem and the scenario.
2. Explanatory understanding. The studies develop an explanatory understanding of the problem based on the investigative objects' experience, judgment, and recognition of this issue. During this process, the researcher should separate himself from his subjective opinions and bias toward the problem.
3. Iterative path. Because the researcher does not presuppose any theory or assumption, the research is initiated without any identified prior thinking pattern. This means that in every step of the research, the researcher must be prepared to make self-adjustments, includes the revising and improving of his understanding of the problem and the scenario.
4. Conduct induction. The conclusion, theory, and understanding of qualitative research are processes of collecting data using various methods in natural scenarios, and as such, the process adopts the bottom-up induction strategy to classify the data and provide a systematic and coherent interpretation of the results. Therefore, the results of a qualitative research are only applicable to the specific scenario; its data are thus specific and cannot be promoted or extended to other situations without restrictions.

Based on the four characteristics, the types of problems addressed by qualitative research can be identified:

1. The problem regarding specialty, which is presented as a special case
2. The problem regarding process, which refers to problems concerned with the occurrence and development of events
3. The problem regarding scenarios, which refers to whole situation problems
4. The problem regarding description, which refers to the descriptions or explanation of the essence and significance of phenomena and events

Qualitative research gathers data through open and non-structured methods and includes pictures, videos, sounds, relevant files, and documents, as well as interviews, surveys, and field notes (Morning 2008; Wang 2015).

Qualitative research adheres to certain procedures:

1. Research design. This procedure defines the phenomena and the issue or the problem to be studied, the purpose and significance of the research, and the selection and application of the methods to be used during the research process.
2. The selection of research objects. During this step in the process, the object of the research that will be most informative is identified and defined, and the research time and place are determined.
3. Data collection. This step in the process consists of conducting observations, interviews, surveys, and object collection.
4. Data classification and analysis. This includes reading the raw data followed by archiving, classifying, generalizing, and analyzing the data. Usually, these analysis tasks can be divided into three types, namely, the preliminary analysis, categorical analysis, and scenario analysis. The categorical analysis identifies the phenomena of significant occurrence and provides concepts and terms to explain the phenomena. The scenario analysis incorporates the data into a natural scenario and describes the people, matter, and events involved in the scenario from a temporal perspective.
5. Result demonstration. This final step demonstrates the results in the form of a report. If there is theoretical content in the results, the relevant concepts and basic principles from the data must be generalized, and a theory must be developed that is based on the results and supported by the data (see hdjay's blog, 2012.6.10, http://blog.sins.com.can/hdjay's).

9.1.3 Panoramic Qualitative Analysis

9.1.3.1 The Origin of the Panoramic Qualitative Analysis

To understand why it is necessary to introduce qualitative research with so much detail when we are exploring the qualitative analysis of the theory of mega infrastructure construction management, a contrast analysis is presented.

As previously discussed, qualitative research is applicable to four types of problems. To understand the role of qualitative research in mega infrastructure construct, these four types of problems are compared with management problems in mega infrastructure construction, especially those concerned with the overall design, the overall decision-making, and the evaluation of mega infrastructure construction management. The comparison reveals a degree of similarity:

1. Problems regarding specialty. The problem of specialty is that the problem has distinct characteristics and an inherent nature when compared with other similar problems in the same genre. In fact, every mega infrastructure construction is unique, and thus, any particular managerial activities and problems in a mega infrastructure construction are special, concrete, and unique. Therefore, when exploring the uniqueness of the management entity, the management theory provides the general principle to be followed. More importantly, human intuition

and all types of illogical thinking are necessary to acquire a complete understanding of the unique management entities in the world (Bjørnholt and Farstad 2012; Tian et al. 2015).

Every specific managerial activity of a mega infrastructure construction is the realization of a complex system, and every complex thing is unique with its uniqueness emanating from its details. Therefore, to know about a specific mega infrastructure construction managerial activity or problem, the details must be examined, and its uniqueness must be compared with other projects in the category of project management. In other words, from the perspective of epistemology, any managerial activity in mega infrastructure construction is neither certain nor random; it is unique. Thus, we have no choice but to choose methods that are effective in the specialty of construction management when selecting a method system. In contrast, methods such as questionnaires are unlikely to reveal the specific details of the management because the questionnaire, as a research method, is a normalization method.

2. Problems regarding processing. The problems associated with processing are problems that affect the development, occurrence, and completion of an event. In fact, any one-specific issue in mega infrastructure construction is a procedural problem because it requires that the managerial activity conducted by the management subject be a complete process that involves proposing and clarifying the problem, analyzing the problem and developing a solution, and revising and implementing the solution. Moreover, because the problem is a process, it means that the managerial activity as a whole is dynamic. As such, the property of being dynamic may evolve toward increased complexity in the management of mega infrastructure construction. Therefore, because simple methods such as questionnaires can only collect data from a single research object at a single point in time, these methods cannot help to discover complex dynamic changes in mega infrastructure construction managerial activities or problems and cannot be used to describe the evolution and occurrence of dynamic changes.
3. Problems regarding the situation. The problem with respect to the situation suggests that the problems are not isolated, but rather, they are closely connected with the environment and the situation. Thus, to achieve a profound and concise conclusion when considering and solving problems, the problems must be examined as part of a broader situation. Mega infrastructure construction management problems can be adequately manifested at this point, as discussed in Sect. 5.1.4, Situation (environmental concepts). "During the overall process of mega infrastructure construction, the construction managerial activity is just similar to each relatively independent but coherent story which happens chronologically. All the stories do involve settings and plots, that is, the scenario. On many occasions, the decisions and organizational researches in the theory of mega infrastructure construction management imply the researches on the scenario and its changes integrated by the engineering environment and the self-adapting behaviors of management subjects"(Rhodes et al. 2010). Therefore, any qualitative research on mega infrastructure construction management problems must consider the context or scenario of the management problem and the interrelation and mutual

effect between the situation and the problem. This not only requires that attention be given to the problem's future situation but also to its past and present situations. In other words, it requires attention be given to the prediction and the reconstruction of the situation, because mega infrastructure construction is, by itself, an important new situation that is embedded in a continuous process involving the past, present, and future. Because the situation assumes such a significant place in the managerial activity of mega infrastructure construction, when researching the managerial activity, it is important to reconstruct, restore, reproduce, generate, and predict the relevant situation as comprehensively as possible and to not be satisfied with obtaining only a part, a fragment, or a profile of the situation. *This methodological principle is termed the panoramic mode*. Hence, the qualitative research method in mega infrastructure construction must sufficiently embody and ensure the *panoramic mode*.

4. Problems regarding explanations. Explaining problems or phenomena is a basic and important function of the qualitative research method. However, the qualitative research of mega infrastructure construction includes many more functions than just this one. For example, qualitative research with respect to mega infrastructure construction includes not only understanding and explaining management phenomena of mega infrastructure construction but also discovering the law of managerial activities, instructing, and management practice. This implies that enhancing and developing the traditional qualitative research method can be enhanced by adding new and stronger functions (Mannay 2010; Shi 2013). For example, systematic analyses of the system complexity or the complex wholeness of mega infrastructure construction management can be conducted, as the function of systematic analysis is far greater than the descriptive and explanatory function of the traditional qualitative research method. This example indicates that the qualitative research method of mega infrastructure construction management must highlight and adequately ensure the capacity and means of systematic analysis.

In summary, the features of research objects of mega infrastructure construction management have been clarified, and they have been compared with the problems to which the traditional qualitative research method is applicable. We then find that the starting point and the technical route design of the qualitative research method highly coincide with the features of mega infrastructure construction management problems. This suggests that, on the one hand, the procedures and details regarding the traditional qualitative research method can be learned and transplanted into a new qualitative research method, to as great a degree as possible, and on the other hand, the ability to manage the procedural management problem, scenario problem, and complex management problem in mega infrastructure construction must be enhanced (Werner 2008; Yang 2003). Therefore, as for the new qualitative research method of mega infrastructure construction management, *we propose that it should be based on the traditional qualitative research method to strengthen the function and significance of the management situation and to further strengthen the analyzing ability of the new research method through which the new panoramic qualitative analysis is developed.*

9.1.3.2 The Basic Premise of Panoramic Qualitative Analysis

The panoramic qualitative analysis for mega infrastructure construction refers to a class of methods incorporated into and applied during a qualitative research of mega infrastructure construction management problems. The panoramic analysis is applied to study a certain problem in a specific mega infrastructure construction management system. Alternatively, it is applied to generalize and summarize the qualitative law and to explain phenomena from the theoretical perspective of mega infrastructure construction management.

The fundamental academic thoughts of this method are as follows:

1. Any specific managerial activities and management problems of mega infrastructure construction are special and unique in the sense that they occur under certain historical circumstances and situations and are part of a unique historical phenomenon and process. These activities and problems share similarities, in a general sense, in that they are subject to people's basic consensus on mega infrastructure construction and to their average ability to solve management problems. However, they also differ from other specific mega infrastructure constructions in some ways. Thus, it is not possible to explain the managerial activities and problems of a specific mega infrastructure construction only by means of the law as it extends beyond the details and characteristics of the construction. Moreover, due to the uniqueness of the situation, it is also not possible to explain the activities or problems by way of a random statistical method. Therefore, to study the activities and problems, the method that focuses on the phenomenon concerned with uniqueness should be used.
2. To be exact, by establishing the time point to be that which the researcher situates, the managerial activities and management problems can be divided into two groups. The first refers to activities and problems that occur prior to the established time point, such as a summary of the management experience or the subsequent evaluation of the utility of the construction, and accordingly, this is called *historical managerial activities.* The latter is called *future managerial activities* and includes such activities as a proposal for a construction program for a mega infrastructure construction, the design of a financing mode, the selection of a construction site, and measures of environmental protection. All of these are related to the quality of mega infrastructure construction management and have significant influence on the quality, safety, and comprehensive utility of mega infrastructure construction.

   (a) The best way to address a historical managerial activity is to consider the problem as it was during the initial situation (environmental situation) of the construction and recreate the complete scenario. This is referred to as *the reconstruction of a historical managerial activity of mega infrastructure construction*. However, it becomes evident that it is impossible to fully and accurately reconstruct the event such that it includes the details regarding space and time as well as all of the scenario elements. Thus, it is necessary to collect all types of relevant data and, through various methods, such as communicating with the relevant subjects, to recreate the historical event or process as comprehensively as possible (Cheng 1996; Evans et al. 2004; Guba and Lincoln 2005). By doing so, the researcher may appear alternately as an observer and a participant in the research.

First, as an observer, the researcher will observe the microcosmic behaviors of subjects who participated in an historical managerial activity, the relationships among them, and the conversion and evolution of their activities. Furthermore, the researcher must form a systematic view of management at the macro level and describe and explain the activity from the quality of wholeness.

Second, to be a participant, the researcher assumes himself to participate in the historical managerial activity. Namely, through direct communication with the subjects at issue or through the classification of the data and files, the researcher constructs simulations of the new possible situations to infer a more powerful process for managing events as well as their possible consequences, thus creating an extension of the qualitative analysis for the historical managerial activity in mega infrastructure construction.

(b) With respect to the problem related to a future managerial activity, it is possible to input a construction managerial activity into a possible future situation in accordance with the principles of management, the historical experience, and the prediction regarding the future situation, especially those that indicate the uniqueness of the construction to fully and thoroughly demonstrate the completeness of the potential future situation. This procedure is called *the prediction for the future managerial activity of mega infrastructure construction*. Accordingly, it is clear that any prediction of a future situation or a construction managerial activity cannot be absolutely accurate. However, it is important to collect as much data as possible and to communicate with as many experts from different backgrounds as possible as only by doing so is it possible to make more complete, more diversified, and more prediction to be more complete, more diversified, and more comprehensible predictions.

Similarly, the researcher will appear as an observer, when based on the historical and present situations, he predicts a future situation in terms of the common development path. Conversely, he will appear as a participant, if on the same basis, he makes presumptions about the scenario family in terms of the many possible development paths that may reflect the researcher's perspective (Loseke and Cahil 2007). For instance, the former may predict the future weather conditions for a construction according to the historical and present weather conditions, along with the knowledge of weather patterns, whereas the latter will make predictions based on the common conditions and abnormal phenomena, including the rare extreme weather conditions to which the researcher attaches significant importance.

To summarize, in a study on mega infrastructure construction management, it is necessary to reconstruct or predict the working scenario (environmental scenario) as comprehensively as possible, so management can represent the uniqueness of the construction and detail the construction as clearly and concisely as possible.

3. The scenario has special meaning in the study of mega infrastructure construction management. Mega infrastructure construction management is a coherent and dynamic scenario process that consists of the management's past, present, and future. Thus, the scenario cannot be viewed only from the perspective of the background and conditions of management nor can a segment of the scenario be perceived as fixed. In other words, *the panoramic qualitative analysis of mega infrastructure construction management requires panoramic research thought*.

   With respect to the qualitative research method, the complex scenario of mega infrastructure construction management is conceptualized and described through various means, and, furthermore, the language used has noncausal logical relations. However, regardless of the reconstruction scenario or the prediction, the panoramic research method that constructs the management situation at multiple levels, dimensions, and scales and thoroughly integrates the managerial activity with the management situation is essential for analyzing and illustrating the quality of the management problem in mega infrastructure construction. Moreover, it constitutes the core of the panoramic qualitative analysis.
4. The panoramic qualitative analysis of mega infrastructure construction has more research functions than the traditional qualitative research method as it not only includes the basic explanatory understanding, but it also includes:

   (a) The explanation for management phenomena in mega infrastructure construction
   (b) The refinements of the regularity of managerial activity
   (c) The predictions of management trends
   (d) The program design for management problems
   (e) The overall assessment for management effectiveness, etc.

These functions, when realized, are representations of the functions of the overall activities of the management subject, especially the management organization with respect to the mega infrastructure construction managerial activities. Furthermore, the realization of these functions is embodied in the systematic analysis of the problems that arise during managerial activities. Therefore, *systematic analysis constitutes another core feature of the panoramic qualitative analysis*.

Thus, it is noted that the systematic analysis mentioned herein stresses the complex systematics of mega infrastructure construction management and an analysis based on the overall scenario of the compound system between the management problem and the environment. Additionally, this cannot be considered only an analysis of a local problem related to management or a problem related to a specific level or stage. This analysis belongs to the complex systematic analysis where in the complexity analysis and systematicness are its core. Thus, when it is compared with the traditional qualitative research method, this new analysis reflects a tremendous advancement in the function.

Accordingly, it is evident that under the instruction of the thinking principles of mega infrastructure construction management theory and the essence of the management problem, the panoramic qualitative analysis not only preserves the basic premise of the traditional qualitative research method, but it also underscores the significant role of the overall scenario of mega infrastructure construction management and system analysis. Thus, with the help of meta-synthesis, a new qualitative research method in mega infrastructure construction management has been developed (Creswell 2003).

Specifically, *the panoramic qualitative analysis is a research method that, when used in the research of mega infrastructure construction management, the researcher either serves as an observer or as a participant who then conducts a detailed investigation in the field and collects the relevant data. Based on the investigation, research, and data collection, the researcher then reconstructs and predicts the scenario where in the problem he has researched lies. Given that the reconstruction and the prediction are systematic and procedural, he will obtain the research result through a systematic analysis that combines reduction theory with system theory.*

The panoramic qualitative analysis focuses on the unique quality of mega infrastructure construction management and requires the integration of the panoramic view and systematic analysis. According to this analysis, the panoramic view represents the systematicness of the managerial activity, whereas the systematic analysis represents the complexity of the managerial activity. Accordingly, the panoramic view provides an adequate illustration of the adaptation principle in terms of the complex systematicness of mega infrastructure construction management in that the panoramic view illustrates the wholeness of the research problem and the systematic analysis illustrates the details of the problem.

It is noted that this analysis should be regarded as a method that is primarily, though not purely, qualitative, considering that the purpose for which it is applied, such as the reconstruction, prediction, or systematic analysis of a scenario, is more commonly associated with computer modeling and quantitative methods intended to ensure the quality of the management. However, in general, these methods are not dominant, whereas the qualitative method assumes a dominant place (Baškarada 2014; Mahoney and Goertz 2006).

9.1.3.3 The Basic Steps of Panoramic Qualitative Analysis

A panoramic qualitative analysis is comprised of many steps:

1. Identify the phenomenon or event to be researched and define the relevant area, time, level, and basic scenario.
2. Define the value of the research, including the theoretical significance and application value, such as its contribution to the explanation of managerial activity and practice, the disclosure of the law and the instruction for practice.

3. Conceptualize the phenomenon and the event to determine its scientific implication and guarantee its development as a complete scientific problem under the theoretical system.
4. Collect the relevant data using all means and methods available. Data collection should be oriented with the definition of the basic scenario as it relates to the research problem and the purpose of the research. Because every mega infrastructure construction has its own specialty, regardless of the historical managerial activity or the future managerial activity, the data collection should closely relate to the construction and the scientific problem with which it is concerned, even though it is not a process of random sample extraction in statistics. In the field of construction management, the data are retrieved from the published literature, the unpublished archival data, videos, material objects, and pictures. However, data can also be obtained from direct or indirect communications with subjects, interviews, and on-the-spot investigations.

   In this step, the researcher plays the role of either an observer or a participant. Regardless of the role he has assumed, his goal is to insert himself into the phenomenon or event. However, the researcher should avoid influencing, based on his preference, the thoroughness of the data collection and objectivity with respect to objectivity of the conclusions he draws from the data.
5. Reconstruct the scenario of the historical managerial activity or predict the scenario of the future managerial activity according to the structure of the phenomenon or event and the meaning of the scientific problem based on the available data. Then, construct, as a further step, the integrated system of scientific problem-scenario reconstruction or scientific problem-scenario prediction, both of which are used separately to study either the historical managerial activity or the future managerial activity.

   Because this is a key step in the panoramic qualitative analysis, it is important to remember that in practice, it is difficult to fully recreate a panoramic scenario. In the beginning, it may be that we seize only a piece or a segment of the scenario that influences the effect of using this method and thus infers that it is necessary to iterate the reconstruction and prediction many times over to improve the correlation between the systematicness of the scenario and the problem.
6. Treat the integrated system of the problem-scenarios a further research object and apply systematic analysis. Systematic analysis, as mentioned here, is a general name for a system of analytical methods that contains extensive content and has its own academic background, procedures, norms, and paradigms; therefore, it will not be discussed in detail in this book. However, it is important to note that the methods and content of the systematic analysis in the panoramic qualitative analysis should be oriented to align with the purpose and the significance of the research.
7. Evaluate repeatedly whether the conclusion of the systematic analysis is true, explicable, and instructive and whether it contributes to the contribution of the analysis, i.e., to the research purpose and its theoretical and practical values.
8. Develop the research report, i.e., the conclusion.

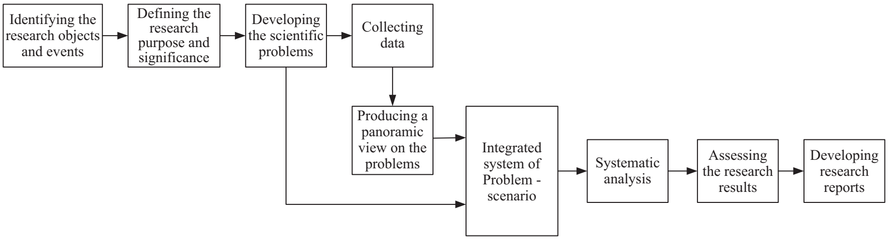

Fig. 9.1 The flowchart of panoramic qualitative analysis

To sum up, the main procedure of panoramic qualitative analysis is presented in Fig. 9.1.

According to the basic premise of the panoramic qualitative analysis as well as its procedure, a summary review for this method can be broken down into six steps:

1. This method is a type of qualitative research method, i.e., centers on the qualitative research method, in the research of mega infrastructure construction management.
2. This method is used primarily to study the problem of quality with respect to specific management.
3. This method embodies the basic technology path of the traditional qualitative research method, and it highlights the unique scenario of mega infrastructure construction management and the function of systematic analysis.
4. This method not only explains the traditional qualitative research method, but it is also responsible for analyzing, predicting, and making decisions relevant to managerial issues.
5. This method has as its foundation the method of case study. Thus the authenticity and explanatory power of the results obtained by using this analysis lack the abstractness and universality possessed by general theoretical research. However, if the reconstruction scenario is sufficiently comprehensive or the range of the future scenario is sufficiently broad, this method will contain more phenomena and complex forms of the integrated system of the problem-scenario. Thus, the universality and generalizability of the final conclusion will be amplified.
6. With the further development of interdisciplinary research, the importance of the integration of the panoramic qualitative analysis with other methods, such as the quantitative method and computer modeling, is recognized day-by-day, and there appear new synthesizing methods for the research of management, such as the method of qualitative-quantitative-scenario analysis.

9.1.4 Two Simple Cases

Two cases are briefly introduced that are concerned with the application of panoramic qualitative analysis in the study of mega infrastructure construction management. The first case addresses a qualitative analysis of the historical managerial activity of a specific construction, and the second is a generalization of the management law, which is based on a qualitative analysis of the historical managerial activity of several specific constructions.

Case 1: A review and reflection of the decision-making process – a history of the Three Gorges Project

The Three Gorges Project (China) is a world famous mega infrastructure construction. In the field of Chinese mega infrastructure construction, the decision-making process regarding the initiation of this construction project extended over an extremely long period of time. Moreover, this project presented the most complex decision problem and the greatest amount of content of any project to date. Though the construction was completed more than 20 years ago, the decision problem relating to it still incurs disagreements, which is rarely seen in the decision activity of mega infrastructure construction on a global scale.

On the one hand, the decision management organization of the Three Gorges Project encountered many concerns with respect to scientific and democratic management that are worthy of discussion, and on the other hand, the decision-making regarding the Three Gorges Project was inevitably influenced by the historical scenario, the decision-maker's ability, and the technology conditions of the time. Hence, decision could be made only under the scenario of the memory and expectations at that time. This emphasizes that, when summarizing the management experiences of the Three Gorges Project, the decision-making process should be reviewed from a historical perspective to provide suggestions about improving mega infrastructure construction management.

Specifically, it is important to begin at the time the decision was made and reconstruct the scenario in such a way that reflects the national, societal, economic, and cultural environments at that time and the decision behavior based on that scenario. Accordingly, it was necessary to integrate the typical decision problem with the scenario into an integrated decision problem-scenario system and recreate the occurrence of the individual behaviors the organizational behavior and the interaction between the two in the decision-making organization. In particular, it is necessary to find an explanation for the decision-making process by observing the details of the decision-making subject's behavior or to investigate and find a way to improve the quality of decision-making through constructing the possible scenario.

Therefore, it is necessary to rely on the published literature, unpublished files, videos, material objects, pictures, and audio materials related to the decision-making in the Three Gorges Project to reconstruct the scenario of the decision-making process. For example, we can reconstruct the macro scenario of the specific decision problems such as sediment control, flood control, and ecological environment protection and reconstruct the micro scenario by obtaining data and conducting interviews with the relevant subjects. This should establish the panoramic decision management scenario of the Three Gorges Project at the macro, meso, and micro levels. A systematic analysis of issues such as changes in the leadership of the decision-making subject, the evolution of the subject structure of the decision-making organization, and changes in the disclosure of the information regarding the decision can then be based on these three levels of the panoramic decision management scenario, and a comprehensive summary of and reflection on the successes and weaknesses in the decision-making of Three Gorges Project can then be formulated.

Case 2: The evolution of the financial mode for long-span bridge construction in China

The long-span bridge refers to the bridge whose multi-hole span is longer than 1000 m or single-hole is longer than 100 m. In the past 30 years, China has experienced unprecedented development in highway bridge construction. By the end of 2014, China had built 7,571,000 highway bridges, of which 3404 were mega highway bridges and 72,979 were long-span bridges. As China has undergone a drastic reformation in its economic system over the past decade, the financial mode for the long-span bridge is also under reformation and diversification. When researching management problems in mega infrastructure constructions such as this, it is not advisable to adopt a random sampling or statistical analysis methodology for the research because, though there are certain physical scale measurements of the long-span bridge, it cannot be inferred that every bridge is of the same model since all of them are neither certain nor random but rather are particular constructions. Thus, the study of the regularity in a certain phenomenon of a group of long-span bridges cannot be made through random abstraction and statistical assumption and testimony. However, we can use the panoramic qualitative analysis to provide a panoramic, systematic analysis of the financial mode in every bridge construction, which will then allow generalization of the analysis.

In recent years, sufficient data on the financial modes of tens of long-span bridges that are located in a dozen provinces in China have been gathered from which the corresponding economic, social, and environmental scenarios have been created, and a systematic analysis from several perspectives as to the relation between the financial mode and the scenario elements, such as space-time, region, economic growth, and managerial behaviors, has been performed. The results of our qualitative research demonstrate the financial modes for long-span bridges in China:

1. There exist distinct regularities in the historical changes of the financial modes for long-span bridge construction in China.
2. With the formation of China's market economy system, the long-span bridge construction in China reveals the characteristic as both a personal product and a public production, with a prospective characteristic as the public product becomes increasingly more obvious.
3. The economic characteristic of the long-span bridge in China determines that the government is the major investor and the market is the necessary supplement.

4. Since the 1990s, the financial mode of China's long-span bridge has gradually developed into a new, diversified structure as one that is government-leading, society-participating, market-operating, and industrial-developing.
5. China has vast territories in which the social and economic development among the east, middle, and west areas is significantly diversified. This diversification and the different purposes of bridge construction give rise to the variation in the function of the government and market in determining a financial mode, which in turn leads to the diversified structure of the financial mode in an area or areas at different times.

The explanation of the qualitative phenomenon and the disclosure of the regularity in the financial mode for mega infrastructure construction are overall results that are derived not from using statistical methods, questionnaires, or the usual case study but from using the panoramic qualitative analysis as the basis and combining it with the inductive method. From this, the significance and function of the panoramic qualitative analysis in the study of mega infrastructure construction management is evident.

9.2 Specialized Method 2: Scenario Farming

The concept of scenario has been well discussed in this book. In Sect. 5.1.4, as a basic concept, the scenario is introduced as a theoretical system of mega infrastructure construction that is intentionally constructed. As the starting point of this construction lies in the complex circumstance of mega infrastructure construction (Brockmann and Girmscheid 2008; Bosch-Rekveldt et al. 2011b), it is not possible to describe the holistic phenomenon based on states or parameter settings. Instead, the concept of scenario must be depicted or demonstrated (Ringland 1998). In Sect. 7.2, the concept of scenario plays a vital role in the evaluation of deeply uncertain decision qualities of mega infrastructure construction, and the robustness of the scenario is used an important index to measure qualities of mega infrastructure construction decisions.

In real mega infrastructure construction management activities, what subjects perceive as real-world scenarios that are occurring or forming are called *instant scenarios*. However, mega infrastructure construction management must not only know about instant scenarios but must also be able to predict future scenarios and even reconstruct past ones (Van Notten and Rotmans 2001). For example, in the process of prior planning certification, analyses and comparisons are needed to conduct different construction programs that require virtual engineering corresponding to the various projects to be considered in future construction scenarios and to form composite system scenarios of mega infrastructure construction circumstance. Additionally, the holistic effects and risks produced by different scenarios must be analyzed, and a comparison of the advantages and disadvantages of various construction programs must be conducted. Furthermore, because a representation of a certain past scenario may be necessary when evaluating certain mega infrastructure construction decisions, it would be better if past scenarios could be rebuilt so the decision behavior selections of management subjects can then be analyzed during the process of re-enacting the scenarios.

Nonetheless, it is concluded that prediction and reconstruction of mega infrastructure construction circumstance scenarios are important research methods in the theoretical studies of mega infrastructure construction management.

In fact, the reproducing of scenarios is always a focused method in management studies. For instance, during the process of studying entrepreneurial strategic decisions, some scholars conduct component analyses of scenarios that enterprises may encounter in the future. On this basis, several important factors are selected and then grouped in such a way that one combination corresponds to one scenario, thus generalizing certain types of scenarios. From these scenarios, the selection of strategies for enterprises can be studied (Hu 2012). Moreover, it is evident that people's technical thoughts are reflected by these scenario generation methods:

1. Assuming that subjects fully understand all of the scenarios and they are certain as to what scenarios will appear, what is the possibility of them appearing?
2. All scenarios can be structured.
3. All scenarios are constructed by subjects, and different scenarios can be achieved by different regulations and parameter settings.

However, scenarios in mega infrastructure construction management theories are much more complicated than these (see Sect. 5.1.4), especially those that are deeply uncertain and that emerge in the context of multiple scales. Thus, as they cannot be generated by such simple methods, exploring new generative methods related to complex scenarios in theoretical studies of mega infrastructure construction management is a critical research task.

9.2.1 Overview of Scenario Farming

In the study of generative methods of mega infrastructure construction scenarios, the reorganization of generative objects, i.e., the most fundamental features of scenarios, should be conducted first.

Scenarios in mega infrastructure construction management activities, regardless of whether they are past, present, or future scenarios, are all holistic behaviors of complex systems that include people, circumstances, and a physical world. Therefore, they are evolutionary, emergent, and self-organized, and they generally include structured, semi-structured, and non-structured components.

From the perspective of research methodology, in social science studies, researchers must describe social systems using certain symbolic systems such as the media and then predict the future development of social systems. In 1988, Ostrom mentioned three symbolic systems that are available to social scientists. He noted that in addition to familiar qualitative methods that can be certified by natural language and quantitative methods described by mathematical language, there is a third research method: computer and programming language. He suggests that the standardization of computers and programming languages can be used to describe thoughts, discuss the past, analyze current scenarios, and make future predictions with the assistance of computers. This methodological principle indicates that based on traditional qualitative and quantitative methods, descriptions, predictions, and reconstructions of mega infrastructure construction management scenarios can be realized through computer technologies. This constitutes the basic strategy for producing mega infrastructure construction scenarios in this book.

In particular, every mega infrastructure construction management scenario is not only complicated, but it is also unique. Meanwhile, the collection of scenarios is limited, with few samples from which to draw. Therefore, it is not possible to predict and discover statistical rules from a large number of known construction management scenario samples. However, based on the foundation of a few valuable scenario samples of construction management and by using computer systems as laboratories, the actual construction management scenario samples and clues can be used as seeds that must be planted, cultivated, and developed. From these, the fruits, i.e., valuable lessons, of various scenarios can be obtained. During the dynamic evolutionary process of developing these fruits and from the types and features of these fruits, analyses, predictions, and reconstructions with respect to knowledge and rules of mega infrastructure construction management scenarios can be conducted. This process is known as the computer simulation method of scenario generation, i.e., the scenario farming method, in theoretical studies of mega infrastructure construction management.

9.2.2 The Basic Interpretation of Scenario Farming

With respect to mega infrastructure construction management theories, the scenario farming method is a new research method and thus requires explanation.

The scenario farming method is used to conduct computer reconstruction and prediction of scenarios under the definition of scenario space by using the scenarios in mega infrastructure construction management activities as its core. The method embeds the scenario space into a type of mega infrastructure construction management phenomena that has the same essence or dynamic mechanism as the foundation of one or more scenario concepts or clues, according to the predefinitions and predictions. In other words, the phenomena are embedded into a certain scenario space.

This method has important significance in the theoretical studies of mega infrastructure construction management because mega infrastructure construction management scenarios are scarce and inadequate. Consequently, it is necessary to farm and cultivate the seeds from a few valuable scenarios according to research purposes and to let them grow and develop to then obtain more possible scenarios that can enrich the cognition of mega infrastructure construction management scenarios.

Next, from the perspective of operational processes, scenario farming method can transport, to some degree, the past and current construction scenarios into computer systems. Hence, controllable and repeatable farming can be conducted via a computer substitute of real construction scenarios. Moreover, this substitute can then reveal both the yesterday and the today of mega infrastructure construction scenarios by examining the growth results. In addition, the unrealistic, virtual tomorrow of construction scenarios can also be constructed in computers with the aim of presenting future scenario images of mega infrastructure construction circumstance composite systems.

Because of the self-organization nature of the forming of construction scenarios, its evolutionary process has certain routes along the backward time axis but uncertain routes along the forward axis. Thus, whereas the current scenarios include past scenarios, the current scenarios may not be totally included in past scenarios. Furthermore, the future scenarios are not entirely included in the past or current scenarios. Accordingly, the future scenario images may be those that were not noticed in the past, were not recognized in the present, or were never predicted. In this way, by discoveries and inferences of tomorrow's scenarios (prospects) as part of the mega infrastructure construction management activities, the possible future of mega infrastructure construction circumstances can be better predicted, which can help prevent harmful scenarios that otherwise may manifest in the future and help realize the future scenarios to which management is optimistically anticipating.

In essence, the mega infrastructure construction scenario is a form of complicated whole behavior systems that includes structured, semi-structured, and non-structured components. However, because of the computer simulation method, the construction scenarios must first be abstracted and symbolized before structured models of the core elements and correlations, i.e., *core scenario or scenario core*, of the scenarios can be built. In this way, computer systems can comprehend and execute farming programs and actions. Accordingly, it can be concluded that the scenario farming method applies structured technical routes that can be calculated by computers to cultivate and grow scenarios. Though is impossible to not lose or not abandon the existed semi-structured or non-structured elements in scenarios, scenario farming uses several approaches to abstract and symbolize, to as great a degree as possible, certain semi-structured and non-structured elements of the scenarios, and it compensates for a scenario loss that is possibly produced by the structuring of researchers' imagery thinking and innovative thinking. Based on the analyses and practices, the scenario farming method is found to be an effective approach for the reconstruction, discovery, and prediction of mega infrastructure construction management scenarios.

Because of various mega infrastructure construction scenario elements that concern society, the economy, natural ecology, and other fields and that evolved as a result of multi-scale time and space, only scenario farming methods that are based on computer systems can exploit the advantages of computers and humans and realize reconstructions and predictions of scenarios' complexities and evolutionary characteristics. Accordingly, the scenario farming method fully represents the meta-synthesis system that combines humans and machines together and focuses on humans in the process of studying complicated management issues.

It is further noted that there are enormous differences between scenario farming methods and common computer simulation approaches. Computer simulations require a certain real system as a benchmark to achieve fidelity. Scenario farming, however, is the simulation of mega infrastructure construction scenario space. Any specific scenario has the features of route-dependence, irreversibility, evolution, and uncertainty or mutagenicity. Thus, it is not appropriate to use just any certain scenario that has been observed or acknowledged as true to balance the rights and the wrongs of the results of scenario farming. Furthermore, predicting which evolutionary route of the scenarios is acceptable or optimal is no longer acceptable. Scenario farming results should be understood in the context of certain assumptions and rules as a scenario area whereby one of the routes that evolved from the real scenarios to the future scenarios formed in the scenario space under the catalyst of mega infrastructure construction complexity and the self-organization function of the mega infrastructure construction circumstance composite system. To the extent of possibility, scenario farming results should be considered true.

9.2.3 Scenario Modeling of Scenario Farming Methods

When evaluating whether scenario farming methods are effective, an important key technology is to conduct the scenario modeling for mega infrastructure construction management. Accordingly, the thinking developments and basic paradigms of scenario modeling among scenario farming methods must be understood.

1. Scenario Modeling Thinking Development of Scenario Farming Methods

   The central connotation of scenario farming methods states that scenario modeling and scenario analysis require the adoption of combinations of the top-down research method and the down-top method. These methods are divided into two phases, namely, the top-down scenario analysis and the down-top scenario modeling (see Fig. 9.2).

   (a) Scenario Analysis: Adopting the top-down methodology, this begins with the overall framework, is continued through the separate modules, and finally results in structured scenarios. Then, the elements, correlations, behaviors, structures, and functions necessary for scenario constructions, including system levels (e.g., administrative divisions, social systems, engineering environment systems, industries, supply chains), subject and organization levels (e.g., proprietors, enterprises, social organizations, governments) (Baccarini 1996; Bosch-Rekveldt et al. 2011a; Xia and Lee 2004), and primitive levels (e.g., subjects' memories, perceptions, preferences, behaviors) are generalized, abstracted, and summarized. These activities are a necessary part of the scenario construction preparations.

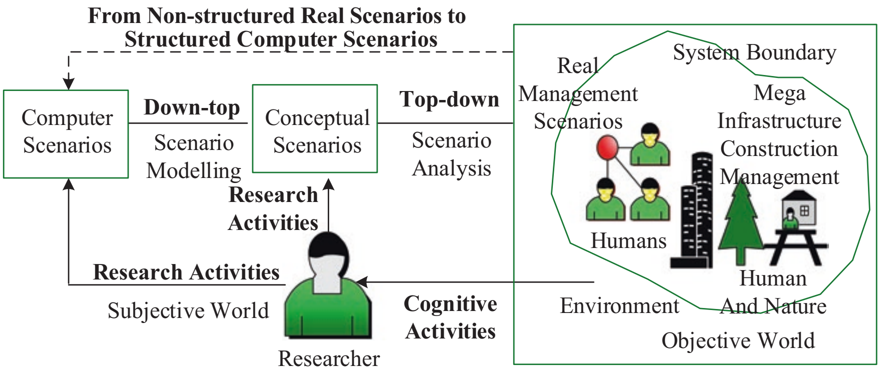

Fig. 9.2 Scenario modeling thinking development of scenario farming methods

(b) Scenario Modeling: This involves converting conceptual scenarios to scenarios that can be realized by computers. During the process of scenario modeling and computer realization, the down-top method is adopted from separate modules and integrations to obtain a holistic emergence of systems at the macro levels by studying individual behaviors at the micro levels. This process can solve the general framework problems of mega infrastructure construction complex management systems and system designs of structures and interfaces. Furthermore, it can be used to conduct analyses of micro issues regarding artificial engineering systems and behaviors from a partial perspective.

The study of mega infrastructure construction management scenarios using the scenario farming method is not only an interactive process of continuous comparisons and advancements in real scenarios and computer scenarios, but it is also a process of continuous improvements and the deepening of actual scenarios. By synthetically applying several theories and methods of social science and natural science and incorporating the human-computer interactions, the scenario farming method simulates the evolutionary paths of the mega infrastructure construction management systems. Finally, using the virtual-actual combination methods and the mutual comparisons and comprehensive evaluations of computer scenarios and real construction management scenarios, the scenario farming method can also extract key factors and important routes that influence evolutions of the mega infrastructure construction management system and improve systematic operations.

2. Scenario Analysis of Scenario Farming Methods
Scenario analysis (Kahn and Wiener 1967; Ishida 2002) is a vital process in the context of scenario farming methods. In the analysis, the first step is to recognize cognitions and conduct abstractions of mega infrastructure construction management real systems and abstract elements, correlations, behaviors, structures, and

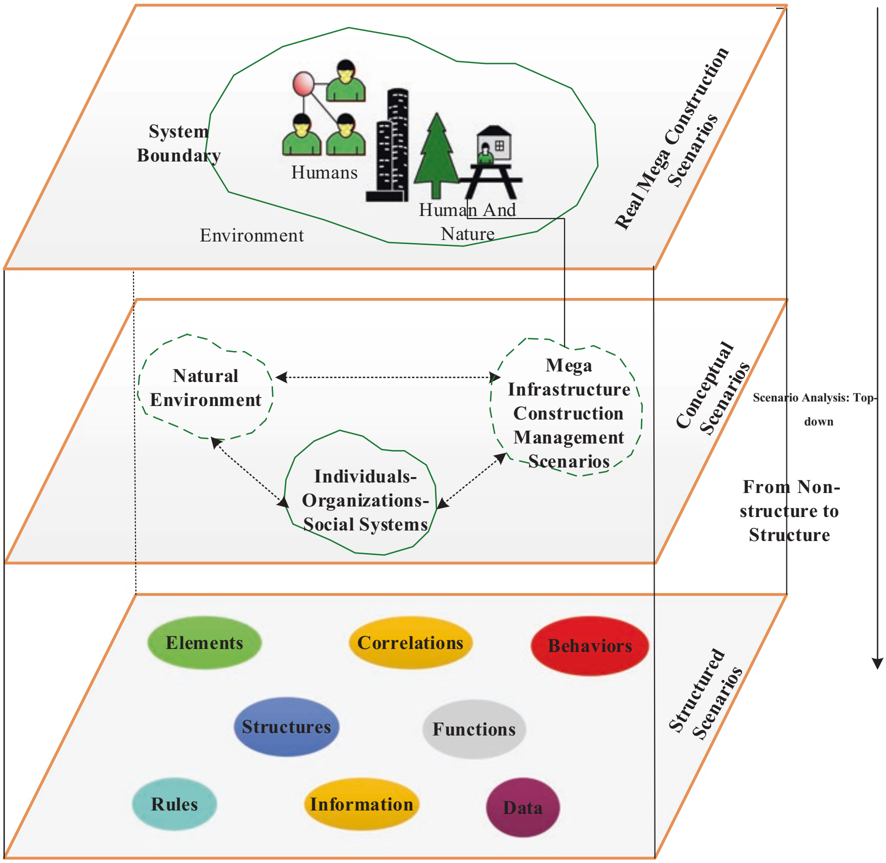

Fig. 9.3 Scenario analysis framework of scenario farming methods

functions of the systems. Then, on this basis, the structured process is conducted on the abstract systems to form conceptual systems. According to the results, it is concluded that the targets of the scenario analysis are the construction management systems, whereas the consequences of analysis are the conceptual scenarios, and the purposes are to provide the necessary conditions for further scenario modeling. The specific process is displayed in Fig. 9.3.

(a) From Real Scenarios to Conceptual Scenarios

Real scenarios of mega infrastructure construction management become conceptual scenarios after being perceived and recognized by researchers. People tend to use both direct and indirect approaches to cognitions of real scenarios. The direct approach refers to forming immediate perceptions and recognitions of real scenarios through the functions of the five senses, namely, sight, hearing, taste, smell, and touch, whereas the indirect approach refers to forming perceptions by obtaining, understanding, and processing others' existing cognitive information regarding real scenarios. In actual scenarios, people usually use a combination of direct and indirect approaches to perceive real scenarios.

Therefore, no matter what approaches are employed to understand mega infrastructure construction management scenarios, certain images and concepts will be formed in people's minds. Hence, mega infrastructure construction management scenarios are abstracted as concept models and knowledge models that are described by qualitative and quantitative methods, with the aim of transforming actual mega infrastructure construction management scenarios into conceptual scenarios in the minds of the researchers. As researchers conduct in-depth analyses and develop perceptions of real scenarios, visualizations and systematizations of conceptual scenarios will gradually be realized. In this sense, the transformation from real scenarios to conceptual scenarios requires a conceptual scenario sequence that is relatively disordered, non-structured, indistinct, and non-optimized though continuously improved and advanced to realize the complicated real scenarios.

In particular, the complexity of real scenarios is the result of researchers using emotional descriptions to illustrate the characteristics of the scenario's external performance, using languages to express critical thinking, and using experiences to establish conceptual scenarios when initially learning about and analyzing the issues. Researchers' abilities to generalize and understand combined with their knowledge and experiences play an instrumental role in this process. Furthermore, these abilities and experiences serve as the foundation for the transformation from conceptual scenarios to structured scenarios that can be reconstructed by computers with further adoptions of standard programs while also providing the strict and delicate definitions of the deep relationships and regularities of scenarios.

(b) From Conceptual Scenarios to Structured Scenarios

Based on the above discussion, it can be concluded that conceptual scenarios perceived from real scenarios are usually characterized by features such as non-structure. Therefore, to reconstruct basic scenarios of mega infrastructure construction management phenomena on computers, researchers must combine the structured conceptual scenarios with the semi-structured or non-structured scenarios using the appropriate methods to compose structured scenarios.

It is further noted that as structured scenarios have a broader meaning than structured mathematic models, they are not equal. For example, certain logical relations and certain rules or laws can be considered as structured. This allows researchers to abstract and symbolize real scenarios and to further extract subjects, behaviors, structures, correlations, and rules of structured scenarios with the aim to structure basic scenarios in mega

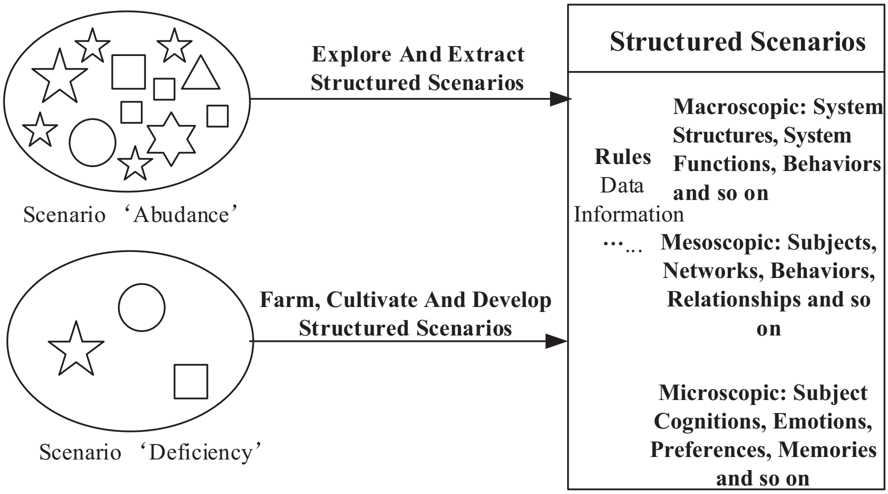

Fig. 9.4 The generation of structured scenarios

infrastructure construction management to make them readable and comprehensible and to clarify the logic relationships of scenario elements for use by computers, as presented in Fig. 9.4.

Meanwhile, it is also necessary to note that the direct starting point of structured scenarios is the gradual extraction of scenario elements from the structured conceptual scenario sequences which are precision and structured step by step, thus making it easier to build models and programs. This, however, requires the selection of the appropriate scenario elements to describe coarse-grained features based on the comprehensive balance of research purposes and analytical abilities, feasibilities, necessities, effects, and efficiencies.

3. Scenario Building of Scenario Farming Methods
When building scenarios for mega infrastructure construction management issues using scenario farming methods, the first step is to define the boundary of the mega infrastructure construction management issue and confirm the study of the management system itself and the environment to which it is most closely related. As used here, the environment refers to the social circumstances and the natural surroundings. The down-top modeling thoughts are usually adopted for mega infrastructure construction management scenarios. Thus, the model includes three levels, namely, primitive levels, subject levels, and system levels, as presented in Fig. 9.5.

(a) Primitive Level
The primitive level is generally comprised of basic elements that describe the subjects' psychological and behavioral activities. As the most fundamental

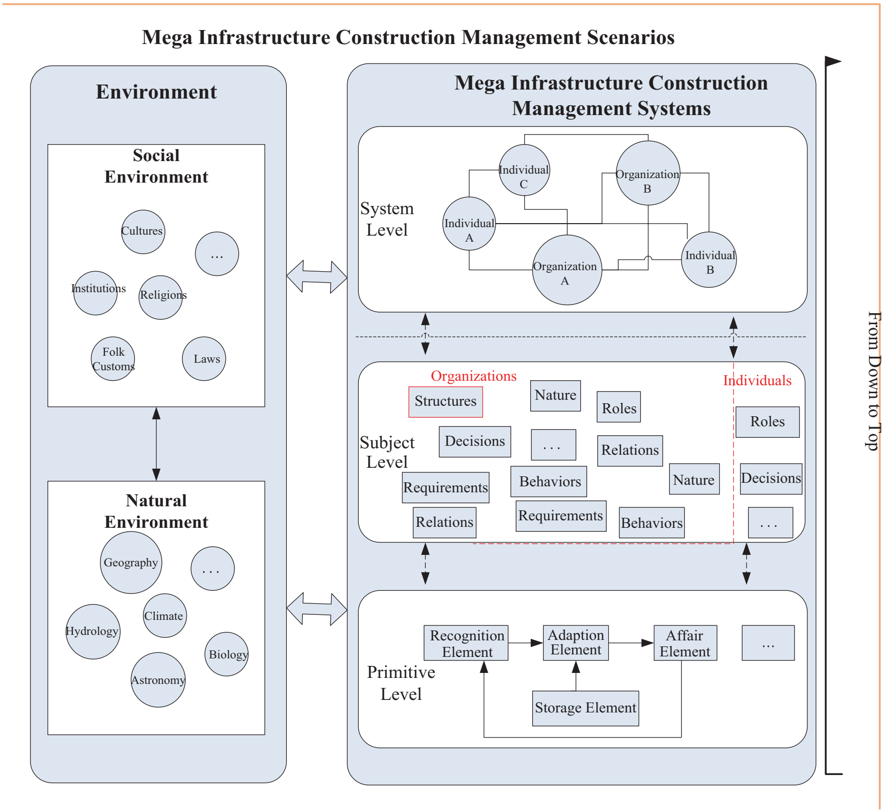

Fig. 9.5 Scenario modeling framework of scenario farming methods

level, it constitutes artificial construction systems and studies evolutionary issues of construction management systems. With the aim to achieve specific purposes, the subjects will constantly adjust their own activities according to the environmental changes. The primitive level of the behavior of the subjects is usually composed of a storage element, recognition element, adaption element, and affair element. The storage element refers to man's memories; the recognition element refers to man's acquisition, judgment, and reorganization of external information and other cognitive behaviors; the adaption element refers to man's studying mechanisms; and the affair element refers to man's actual behaviors after making decisions on the basis of memories, recognitions, and studies.

At the primitive level, combined with the information stored in the subject storage element and under the function of the subject adaption element, the subject recognition element performs cognitive processes that involve the circumstances, subject layers, system layers, and other information that has been input externally. This ultimately results in the intentions of the actual behaviors being represented by the subject affair element. Accordingly, individual behavioral decisions expressed by intelligent agents can be regarded as the selections that are made through integrations and combinations of their own properties, behavioral preferences, memories, and other information under certain boundary conditions, according to the circumstances and the external influences of other intelligent agents. This type of selective behavior includes input and output that can be represented by the encoded form in the computer. The collection, which is composed of several selective coding schemes, constitutes psychological and behavioral characteristics of a certain intelligent agent at a specific point in time. These data can be duplicated via imitations, transmitted via studies and mutated via attempts. They may also be eliminated as a result of various factors. The intelligent agent's primitive level reflects, through different methods, its internal evolutionary process.

In scenario farming methods, the purpose of the construction of the primitive level of intelligent agents is to build a mental model of intelligent agents that is then used to describe the psychological and cultural factors that can influence subjects' decisions. These factors include physiology, instincts, psychology, preferences, pursuits, imagination, and emotional activities of intelligent agents.

(b) Subject Level

The subject level primarily describes the behavioral characteristics of the subjects of the mega infrastructure construction management systems. Subjects include individuals or organizations in the mega infrastructure construction management systems. With respect to individuals, the subject level usually includes the nature, roles, requirements, relationships, decisions, and behaviors of the individual. The nature of the individual refers to comprehensive abilities, intellectual abilities, and personality type. Subjects in mega infrastructure construction establishment and management include proprietors, contractors, and suppliers. The requirements of the subject are used to describe the individual's goals and needs. Subjects' relationships include partnerships, friendships, and game relationships between and among proprietors, contractors, and suppliers. Subjects' decisions involve the process of selecting the best solution from among several options and include investment decisions, contractor choices, among others. Subjects' behaviors refer to the actions of subjects during specific circumstances according to their roles, relationships, requirements, and natures. For example, the suppliers choose to raise the price when the supply does not meet the demand. Furthermore, in some cases, proprietors may form an alliance with contractors to gain illegal benefits.

For organizations, the subject level not only includes the organization's nature, roles, requirements, relationships, decisions, and behaviors, but it also includes the organizational structures. The organization's properties and behaviors are similar to those of individuals. However, organizational structures refer to the internal hierarchical relationships, such as the vertical leader-member relations as well as the lateral relations.

(c) System Level
The system level of the mega infrastructure construction management systems is part of the system's macro level. The focus is on the relations between individuals, between individuals and organizations, and between organizations. The macro holistic behaviors exhibited by the system levels emerge during the interactive process of micro individuals and organizations at the subject level and the environment. The system levels of mega infrastructure construction management systems are composed of a series of subsystems.

(i) Subsystem of Environment. This subsystem describes the environment and its changes with respect to a specific mega infrastructure construction management system.
(ii) Subsystem of Resources. This subsystem describes the natural resources and social resources involved in the study of mega infrastructure construction management systems, such as land resources, different types and forms of energies, human resources, financial resources, information resources, and equipment resources. In most cases, resources are considered to be limited.
(iii) Subsystem of Social Correlations. This subsystem describes the dynamic relational network structure that is formed by separate independent decision-making subjects in mega infrastructure construction management systems through work distribution, cooperation, competition, communication, and other mega infrastructure construction management activities.
(iv) Subsystem of Goals. When studying mega infrastructure construction management systems, many issues must be considered to realize the final goals. Such issues include construction decision purposes, management objectives, and target optimization.
(v) Subsystem of Information. This subsystem describes representation forms, transmission modes, and information categories of public and private information that requires attention.
(vi) Subsystem of Intelligent Agents. This subsystem corresponds to the intelligent subject level and is generally used to describe the behavioral evolutionary processes of various intelligent agents.

The above subsystems incorporate the down-top modeling framework of scenario farming methods. This framework can be refined or extended according to the specific management issues.

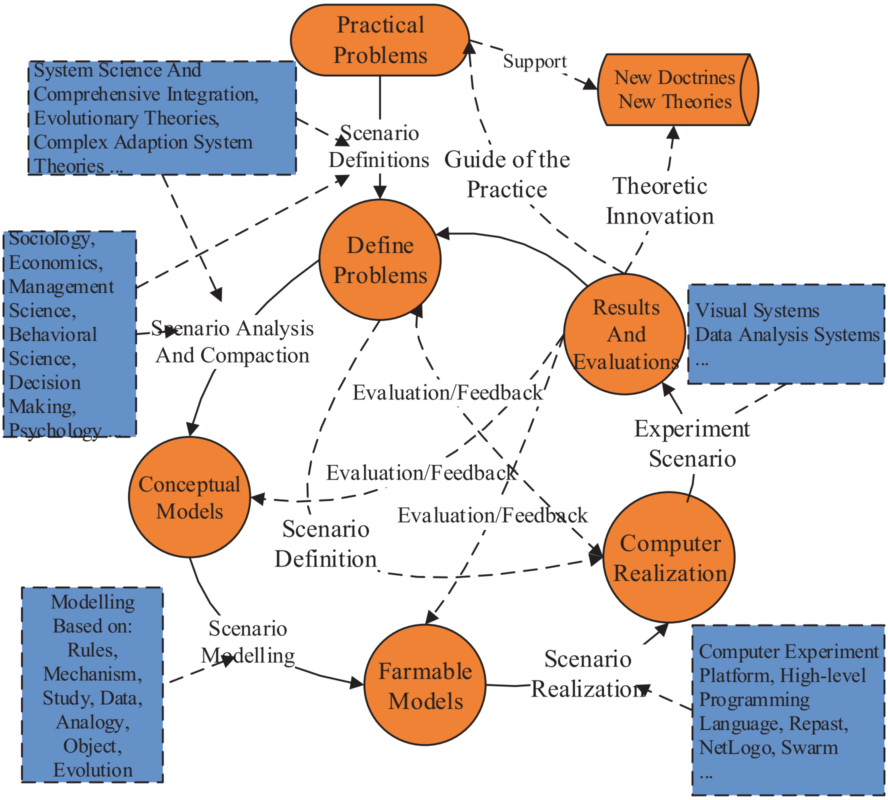

Fig. 9.6 Research paradigms of scenario farming methods

9.2.4 Research Paradigms of Scenario Farming Methods

For the objectivity and credibility of the results to be guaranteed, the scenario farming methods must be implemented under standard research paradigms. These research paradigms usually include five important features, namely, definitions of research scenarios, formation of conceptual scenarios, establishment of farmable models, computer realization of scenario farming models, and evaluations and comparisons of farming results. The process is presented in Fig. 9.6.

1. Definitions of Research Scenarios
   With respect to scenario farming methods, the first step is to define the research questions, i.e., the research scenarios. The research scenario definitions include determining the research objects and their types, identifying the perspectives and features of the research, defining the temporal and spatial characteristics of the

research objects, and setting emulations of final goals. Furthermore, the research objects must be defined according to their spatial features, time attributes, environments, and boundaries, i.e., natural environment, social environment, and environmental patterns.

2. Formations of Conceptual Scenarios
During the process of scenario farming, the formations of conceptual scenarios require researchers to consider construction management issues and then structure the objects' environments and behavior conditions selectively according to the objects and their purposes (Williams 1999; He et al. 2014). Accordingly, this forms the basic assumption of farming that is established on the basis of certain demonstrated or proved principles, common senses, and statistical rules in construction management research, and it functions as the foundation of scenario farming method research.
3. Establishments of Farmable Models
As one of the computer models, the scenario farming model should be able to express, easily and directly, complex scenarios of mega infrastructure construction management systems and correlations between subjects. Furthermore, the model should also allow people to research issues under more advantageous conditions than the original ones. That said, during the process of designing scenario farming models, several key points must be carefully considered.

    (a) Modeling of System Environments. Both the natural and social environments are important influencing factors of management systems for subjects. Therefore, relations between system environments and subjects should be considered during the modeling process.
    (b) Modeling of Subjects. The abstraction from actual systems to computer models is a vital foundation for the realization of scenario farming methods. Farming models are not the absolute replications of mega infrastructure construction management activity scenarios. Instead, they are selectively abstracted scenario features that are creatively expressed when establishing scenarios.
    (c) Designing of Subject Evolution Rules. The subject is the center of the scenario, and the design of the subject behavior rules are the key to the farming modelings. Under the constraints of subject behavior rules, subjects reveal evolutionary tendencies of systems through continuous iterations over several periods in the system environment.
    (d) Designing of Farming Models' Statistical Structures. There are various evolutionary forms for subjects in scenario evolutions, including data interchanges between subjects and between subjects and environments (Ducot and Lubben 1980; Godet and Roubelat 1996; Robinson 2002). These data interchanges of scenarios can be regarded as operations between statistical structures. Descriptions of suitable statistical structures can be adapted to reveal the mega infrastructure construction management system structure and to solve scenario farming method questions such as "what to farm" and "how to farm."

(e) Data Analysis and Visual Representation. A substantial number of intermediate results will be produced during the evolutionary process of farming, and many significant illuminations and implications can be obtained when analyzing these intermediate results. During this process, specific expressions of faming must be vividly presented on computers in ways that involve the establishment of a visual farming space that allows people to observe evolutionary farming processes more intuitively and reveal evolutionary farming rules more clearly.

4. Computer Realization of Scenario Farming Models

   Computer technologies are significantly involved in the realization of scenario farming methods, including establishing scenario farming environments, variables, boundary conditions, key algorithms, calculation formulas, and visualizations of simulation results. The realization process usually adopts down-top research methods. Starting with the primitive level, which determines intelligent agents, intelligent agents should continue to study according to the changing environment, adapt their respective behaviors so they interact with each other, and finally lead to farming evolution.

5. Evaluations and Comparisons of Farming Results

   In most cases, the scenario farming results are a series of data and charts. Hence, analyses, evaluations, and comparisons are an important part of the scenario farming method because they are linked directly to the research results.

After analyzing the results, conclusions regarding farming studies can be drawn based on inductions, summaries, and comparisons between the real scenarios and the farming scenarios. On the one hand, these conclusions can be applied to the practice and can guide the practice. On the other hand, they can also form new doctrines and theories.

9.2.5 A Scenario Farming Example for Decision-Making in Construction

Considering computers as laboratories, scenario farming methods cultivate the alternative version of mega infrastructure construction management systems, i.e., artificial mega infrastructure construction management systems on computers. In addition to using an actual issue as the basic scenario, scenario farming methods conduct scenario reconstructions and prediction studies in artificial mega infrastructure construction systems to explain mega infrastructure construction management phenomena, find explanations and rules behind actual mega infrastructure construction management phenomena, and reveal operational rules of mega infrastructure construction management.

The example of scenario farming of China's Three Gorges Dam Project shipping decision is used to illustrate this method.

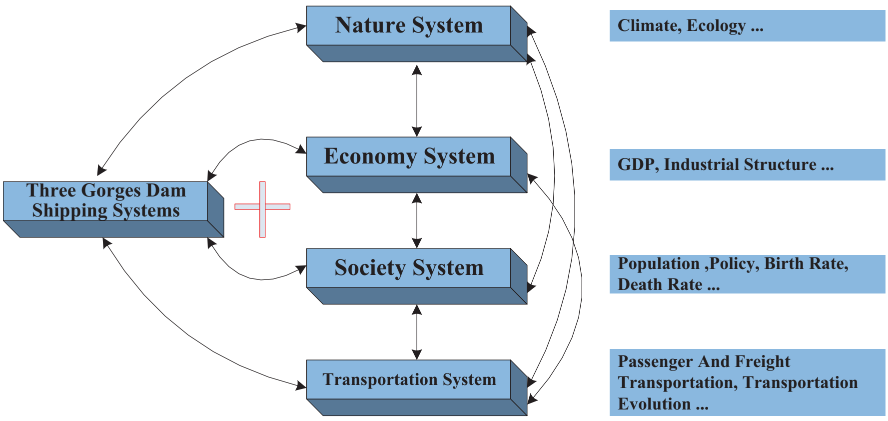

Fig. 9.7 The society-economy-nature compound system of Three Gorges Dam

9.2.5.1 Definitions of Research Scenarios

The construction of China's Three Gorges Dam brings many benefits, including shipping, electricity generation, and flood prevention, that promote the economic development of the Yangtze River. However, as the economy is continuously developing, the cargo throughput of Three Gorges shiplock has been continuously increasing as well. In 2011, the cargo throughput was one billion tons, thus reaching and exceeding the originally intended throughput determined 19 years early. According to the media reports, with the annual increase in freight volumes of the Yangtze River shipping, the crowding phenomenon of lockage has been normalization. Moreover, the problem is becoming increasingly worse, thus creating a shipping bottleneck on the Yangtze River.

The shipping system of the Three Gorges Dam is combined with nature, the economy, society, transportation, and other systems to form the compound Three Gorges Dam-society-economy-nature system. This system is displayed in Fig. 9.7. This compound system reveals, to some extent, the deep uncertainty in management activities.

During the process of demonstrating the Three Gorges Dam shipping, engineers proposed shipping development requirements for the Three Gorges Dam Project and designed the throughput capacity of the shiplock based on predictions about the Chuanjiang River shipping volumes, as presented in Fig. 9.8. From this, it is determined that the foundation of the Three Gorges Dam shipping decision reveals the prediction of transportation construction scenarios.

However, the deep uncertainty of the society-economy-nature compound system of Three Gorges Dam results in relatively large errors between the original predictions of the future transport scenarios and the subsequent actual scenarios. Many factors are responsible for this phenomenon. One important reason is that people lacked the adequate capabilities to predict scenarios at that time.

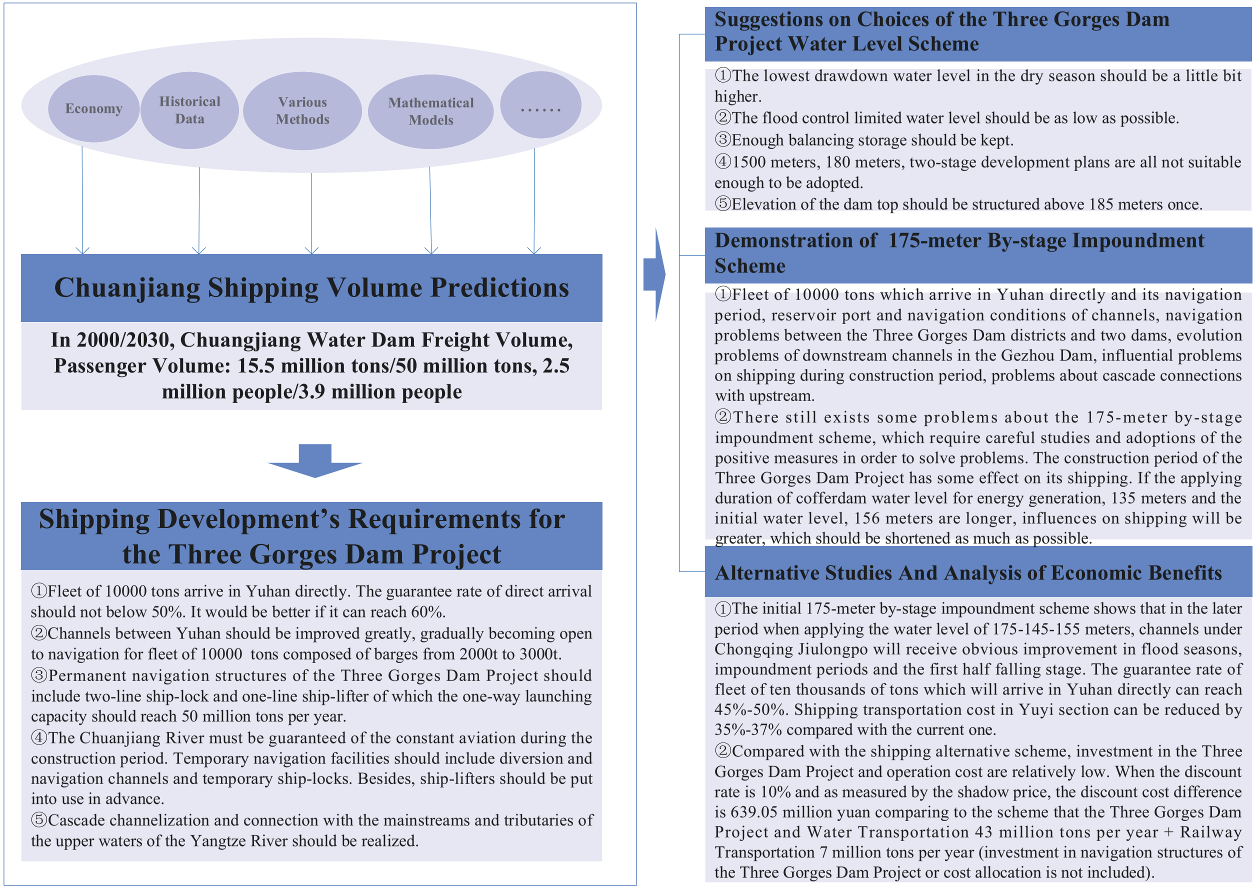

Fig. 9.8 The demonstration process of the Three Gorges Dam shipping

Currently, different conditions of passenger and freight volumes in the regional Three Gorges Dam areas are now simulated in a way that incorporates many uncertainty factors through scenario farming methods. This differs significantly from the prediction methods of the 1990s, the initial period of construction planning. Finally, to demonstrate the significance of prediction methods that are based on scenario farming, the results of the scenario farming are analyzed and compared to actual scenarios.

9.2.5.2 Formations of Scenario Farming Schemes

Specific schemes are adopted and combined with top-down schemes, i.e., from the whole to the separate modules, and down-top schemes, i.e., from separate modules to the whole to perform scenario farming. As presented in Fig. 9.9, according to the research routes, knowing about the society-economy-nature compound system of the Three Gorges Dam, a top-down scenario analysis is conducted. Adown-top scenario is then built to form the artificial circumstance of the compound systems.

9.2.5.3 Establishment of Farmable Models

Farmable models are those models that can farm on computers and cultivate scenarios. Hence, they are able to express correlations between the complicated scenarios of the Three Gorges Dam shipping systems and subjects' behaviors, thus leading to the adoption of approaches that are better than the traditional ones to study this issue. Several key points regarding the modeling must be noted:

1. Modelings of System Circumstances

   First, the compound shipping system model of the Three Gorges Dam can be built at the macro level, and the macro characteristics of the entire shipping system can be described through this model. The system's circumstances in the compound shipping system of the Three Gorges Dam include the society, economy, nature, transportation, intelligent agents, and other subsystems.

   The first step is to build models of the various subsystems according to the system circumstances given that different circumstance factors greatly influence freight volumes.

   (a) The social subsystem is a complicated social network composed of various relations between subjects in society. For example, birth policy, household registration policy, and urbanization rates have effects on the size of the population and on population migration, which may further influence the changes in the quantity demands of passenger and freight transportation passing through the Three Gorges Dam.
   (b) The economic subsystem refers to the economic development and the evolutionary process of seven provinces and two cities along the Yangtze River Basin. By analyzing the endogenous factors of the economic increase, the

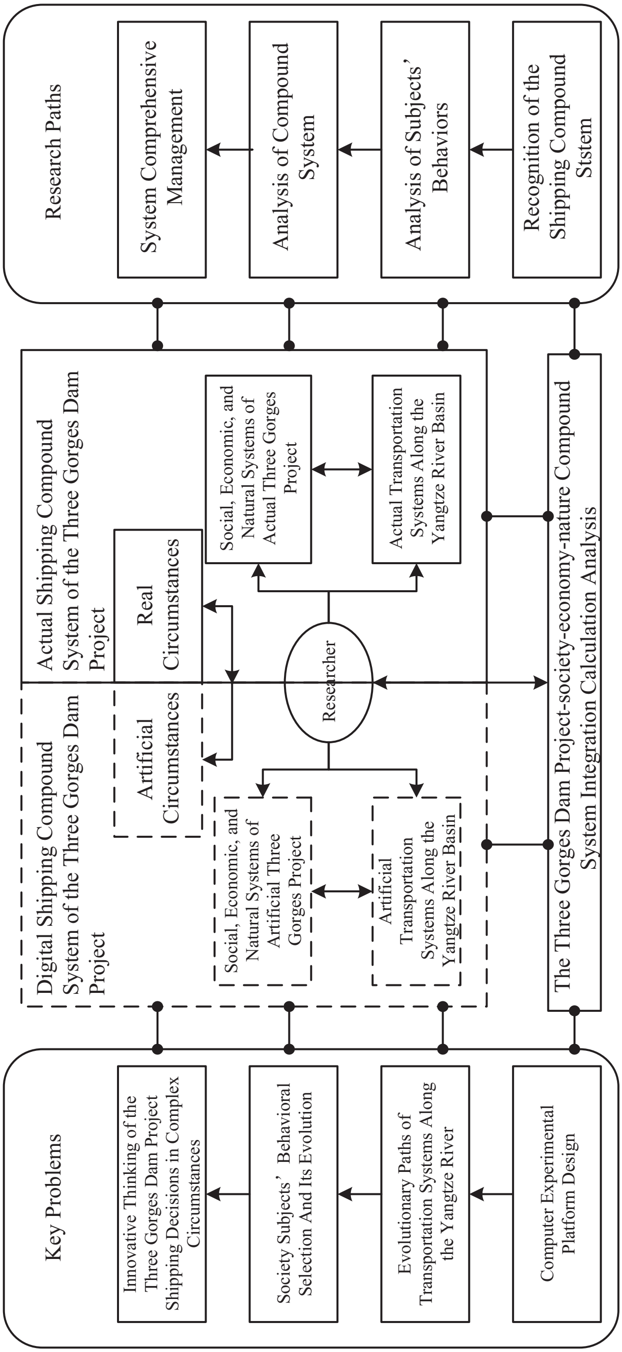

Fig. 9.9 The scenario farming scheme of the Three Gorges Dam Project shipping decision study

endogenous economic system models can be structured to include the aggregate economic volume, industrial structure, and size distribution, which further influence the changes in passenger and freight transportation of the Three Gorges Dam.

(c) The natural subsystem refers to the influence of the ecosystem, climate, and other natural factors of the Yangtze River on the navigational conditions of the Three Gorges Dam.

(d) The transportation subsystem refers to the abilities and changes in the transportation network, which includes the nodes of the Three Gorges Dam Project.

2. Modelings of Subjects

The intelligent agent subsystem in the compound shipping system model of the Three Gorges Dam Project must establish a model to describe the characteristics of participants' behaviors in the passenger and freight transportation system of the seven provinces and two cities along the Yangtze River Basin. Based on the modeling methods of the intelligent agent, subjects' properties, behaviors, local circumstances, and other factors will be depicted with the aim to describe those factors that influence subjects' choices of using shipping as a means of passenger and freight transportation to pass through the Three Gorges Dam.

3. Designs of Subjects' Evolutionary Rules

Based on the modeling of system circumstances and subjects, correlations between system circumstances and subjects must be considered. As such, it must involve the design of the evolutionary rules of subjects' behaviors. Whereas subjects are the core of the scenarios, the design of the subjects' behavior rules is the key to scenario farming models. Under the constraints of subject behavior rules, subjects experience the continuous iteration of several periods in system circumstances to reveal the evolutionary tendencies of systems and describe the various evolutionary processes of multi-intelligent agents.

Using the subject utility selection model as an example, this model describes how transportation users select feasible route plans. Based on random utility evaluation principles, the specific realization is defined by the following formula:

$$\begin{aligned} U_{i,j} &= u_{i,j} + \varepsilon \\ &= \alpha_i \times \mathrm{Cost}_j + \beta_i \times Time_j + \omega_i \times Hap_j + \varepsilon \end{aligned} \tag{9.1}$$

$$\mathrm{Cost}_j = dis_j \times R_j \tag{9.2}$$

$$Time_j = dis_j / v_j \tag{9.3}$$

$$pre(agent_i) = \begin{cases} 1 & rev(agent_i) \le GDP1 \\ 2 & GDP1 < rev(agent_i) \le GDP2 \\ 3 & rev(agent_i) > GDP2 \end{cases} \tag{9.4}$$

$$p\left(choice = j\right) = \frac{e^{u_{i,j}}}{\sum_{m=1}^{N} e^{u_{i,m}}} \tag{9.5}$$

Here, $u_{i,j}$ in Formula (9.1) refers to the utility evaluation of the transportation demander i on the No. j transportation scheme, and it includes two parts, namely, constant utilities and random effects.

(a) ε is the random influence factor of the utility evaluation of subject i, which follows McFadden's (1973) Weibull distribution assumption.
(b) $u_{i,j}$, which is obtained from the specific calculation of various properties of subjects, is the subject's utility toward transportation schemes. For example, transportation cost (*Cost*) and transportation time (*Time*) must both be considered in freight and passenger transportation. The two properties are obtained from the calculation of Formula (9.2) and Formula (9.3). *dis* refers to the transport distance, and R and v, respectively, represent the rate of various transportation schemes and the transport speed of vehicles, which are related to the vehicles (e.g., train, waterway, automobile) selected by the transportation schemes. The property *Hap* varies from passenger transportation to freight transportation. With respect to passenger transportation, it refers to the comfort level that transportation schemes bring to the subjects, whereas for freight transportation, it refers to the reliability of transportation schemes. In the process of farming, this index is assigned differently according to the different selections of transportation vehicles. The vector (α, β, ω) is the weight of subject i on the property vector (*Cost*, *Time*, *Hap*), and the maximum of the three weights reveal the subject's preference for a certain property. To express the heterogeneity of the subject's preference, the subject's preference is assumed to be relevant to the per capita GDP level at that point in time. The specific assumption is presented in Formula (9.4). 1, 2, and 3, separately and, respectively, represent the subject's preference for *Cost*, *Time*, and *Hap*. *GDP*1 and *GDP*2 are the data set by the experiments. p (choice = j) in Formula (9.5) is the probability of subject i selecting No. j transportation scheme according to McFadden's (1973) logit distribution model.

4. Farmable Modelings

Parts 1 and 2 build the shipping compound system model of the Three Gorges Dam Project at the macro level where part 3 designs evolutionary rules for the multiple subjects in the shipping system of the Three Gorges Dam Project at the micro level. These models, however, could not adequately farm the selected scenarios. Consequently, a farmable process of the models must be conducted.

There are various evolutionary approaches for subjects in scenario evolutions, including the data interchange between subjects and between subjects and circumstances. Through these data interchanges, calculable models of key variable shipping, similar to that presented in Fig. 9.10, can be formed. Furthermore, associated variables can be farmed based on this model, namely, the shipping transportation volume.

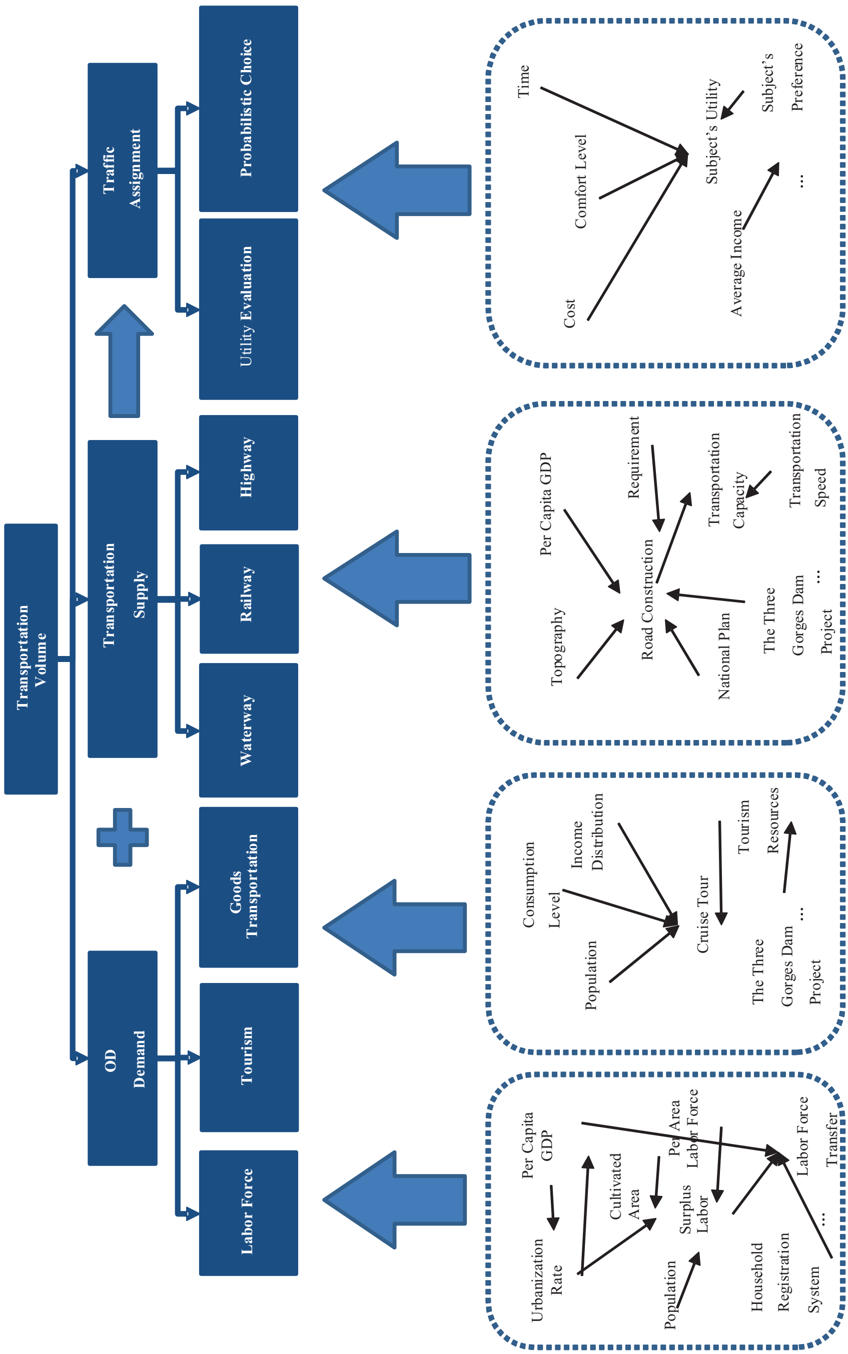

Fig. 9.10 Calculable model of key variable shipping transportation volume

We can conclude from Fig. 9.10 that the key variable, shipping transportation volume, is obtained from the calculations of three modules, namely, OD demands, traffic supplies, and traffic assignments. The major process involves several well-defined steps.

1. OD Demands. According to the establishment of economic systems, natural systems, and social systems and through endogenous modelings and analyses of urbanization rates, labor transfer, per capita GDP, populations, and other factors, the OD demands of freight and passenger transportation in seven provinces and two cities along the Yangtze River Basin are obtained.
2. Traffic Supplies. According to the establishments of economic systems, natural systems, social systems, and transportation systems and through endogenous modelings and analyses of per capita GDP, evolutions of road networks, and other factors, information regarding traffic supplies on waterways, railways, and highways in seven provinces and two cities along the Yangtze River Basin are obtained.
3. Traffic Assignments. According to the establishments of principal subjects, evolutionary rules of subjects, and analyses of cost, time, subject utility, subject preferences, and other factors, predications from the data about the shipping volume of the Three Gorges Dam Project can be made.

The specific farmable process that uses the OD demands module in freight transportation as an example is introduced, and its main idea is divided into several parts:

1. The Analysis of Influential Factors of Freight Transportation

   The first step is to analyze the influential factors of freight transportation in the nine provinces and two cities along the Yangtze River Basin. These factors include mineral products and other natural resource storages, natural factors, regionally economic development and scales, changes in industrial structures, politics, economic systems and policies, population growths as well as changes in the local freight transportation over the years. Endogenous models should be built according to the varied features of freight transportation, and the models of coals, iron mines, phosphate rocks, mine construction materials and the five goods should be constructed separately.
2. The Analysis of Influential Factors of Various Goods

   As there are different weights regarding the influential factors of the demand of each type of goods, an analysis directed at the influencing factors of different goods demands should be conducted.
3. The Demand Model of Various Goods Nationwide

   Based on the analysis of influential factors of goods demands, the endogenous model should be built around the five types of goods demands in our nation.
4. The Analysis of Goods Demands in Nine Provinces and Two Cities along the Yangtze River Basin

   By combining the analyses of economic development scales, natural factors, industrial structure changes, population growth, and other factors in the nine provinces and two cities, the demands for these goods can be obtained on the foundation of the modelings of the (national) five types of goods demands.

5. Goods OD Demands in Nine Provinces and Two Cities along the Yangtze River Basin

Supply models of the five types of goods are built according to analyses of the producing areas and the processing areas. In addition, combined with the demand model (4), OD demands of the five types of goods in the nine provinces and two cities can be obtained.

9.2.5.4 The Realization of Scenario Farming Models on Computers

Based on the farmable models, corresponding scenario clustering can be farmed through scenario visualization and the technology of data analysis (Schwartz 1991; Van der Heijden 1996).

1. Designs of Experimental Variables and Initial Data
   The shipping system of the Three Gorges Dam Project was built based on the analyses of conceptual models. This system includes more than 600 variables of economic, social, and natural systems and other areas. Because of the huge number of variables, this case uses partial variables of economic systems as examples (Tables 9.1, 9.2, and 9.3).
2. Definitions of Experimental Boundary Conditions
   The operation cycle of scenario farming for the Three Gorges Dam Project is 50 years.
3. Core Algorithms
   Because the farming process involves several modeling parameters for the shipping systems, this case selects recursion algorithm to be used in the generation of

Table 9.1 List of partial variables of economic systems and initializers

Variable No.	Mathematical symbol	Descriptions	Initializer
1–9	GDP_i	GDP of the no. *i* province	Determined according to the data of various provinces in 1990
10	*Rate_GDP*	GDP growth, setup according to different scenarios	{0, 0.05, 0.10, 0.15, 0.20}
11–19	Re*v_Coal*$_i$	Coal storage in different provinces	Determined according to the data of various provinces in 1990
20–28	*Cost_rate*	Cost coefficient of various transportation vehicles	{0.03,0.10,0.18}
29–38	*City_rate*$_i$	Urbanization rates of various provinces	Determined according to the data of various provinces in 1990
39–48	Re*venue*$_i$	Annual revenue in various provinces	Determined according to the data of various provinces in 1990
49	*Labor_ efficient*	The amount of labor force needed in per unit cultivated land	{1/3,1/5}

Table 9.2 List of partial variables of social systems and initializers

Variable No.	Mathematical symbol	Descriptions	Initializer
1–9	POP_i	The population size of the no. i province	Determined according to the data of various provinces in 1990
10	$Rate\_Birth$	The birth rate, setup according to scenarios	{0,0.05,0.10,0.15,0.20}
11	$Rate\_Death$	The death rate, setup according to scenarios	{0,0.05,0.10,0.15,0.20}
12	ρ	Preferences of subjects' properties, satisfying a certain evenly distribution	[0,1]
13–15	$Velocity_i$	Transportation speed of various transportation vehicles, existing possibilities of acceleration	{40,80,120,150,200,250}
16–123	$Flag_{ijk}$	Whether the no. k transportation vehicle is practicable from the no. i province to the no. j province	{0,1}

Table 9.3 List of partial variables of natural systems and initializers

Variable No.	Mathematical symbol	Descriptions	Initializer
1–36	Dis_{ij}	The distance from the no. i province to the no. j province, a fixed value	
37–45	$Rain_i$	Precipitation amount of various provinces	Determined according to the data collected in 1990
46–54	(lat, lon_i)	Longitude and latitude of various provinces, a fixed value	
55–63	$(Water\_Level_i)$	Water levels of all the Yangtze River sections	Determined according to the data collected in 1990
64–72	Arg_S_i	Cultivated areas of various provinces	Determined according to the data collected in 1990

subject route schemes. This algorithm solves selection problems of subjects' practicable route schemes in the initialization process, which is marked by $Flag_{ijk}$ in the modeling. All practical schemes can be obtained using the recursion algorithm between the places. Considering the case from Wuhan to Chongqing as an example, the results are presented in Table 9.4.

4. Visualization of Scenario Farming Systems

Fig. 9.11 displays the scenario farming realization interface.

Table 9.4 Table of optional schemes from Wuhan to Chongqing

Scheme No.	Specific scheme
1	Wuhan- > Chenglingji- > Changsha- > Three gorges project- > Chongqing
2	Wuhan- > Chenglingji- > Changsha- > Chongqing
3	Wuhan- > Chenglingji- > Three gorges project- > Chongqing
4	Wuhan- > Chenglingji- > Chongqing
5	Wuhan- > Three gorges project- > Chongqing

Fig. 9.11 The scenario farming realization interface

9.2.5.5 Evaluations and Comparisons of Farming Results

Through scenario farming methods, descriptions, predictions, and reconstructions of the Three Gorges Dam Project shipping scenarios are realized with the help of computer technologies and based on traditional qualitative and quantitative methods.

In the shipping compound system of the Three Gorges Dam Project, changes in shipping volumes of Chuanjiang are affected by several uncertainty factors, such as goods demands, goods supplies, traffic assignments, ship types, and channel conditions. Combinations of these uncertainty factors constitute scenarios. However, combinations constituted by different values of different uncertainty factors vary from scenario to scenario. Many of the different scenario structures include past, present, and future scenario spaces. This study conducts scenario farming by adjusting the values of the uncertainty factors in the various combinations.

Considering the uncertainty factor of “abilities of per capita GDP growth,” scenario farming can be conducted by changing the transportation systems of the Three Gorges Dam Project. Thus, the transportation systems of the Three Gorges Dam Project, passenger and freight transportation volumes, transportation means of the project, and evolutions of ship types and freight and passenger transportation types under the condition of different abilities of per capita GDP growth are analyzed. For example, the annual freight transportation volume in the Three Gorges Dam Project

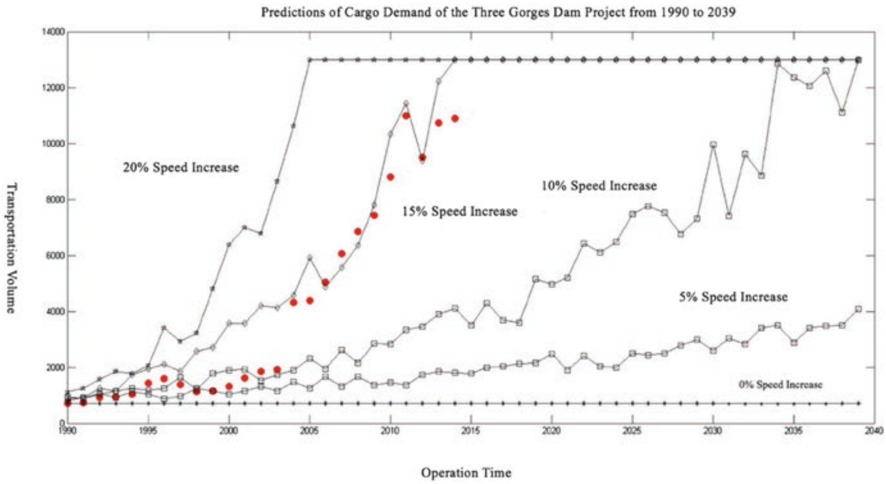

Fig. 9.12 Predictions of demands in freight transportation volumes of the Three Gorges Dam Project from 1990 to 2039

areas is approaching 130 million tons, the evolution forms of freight transportation volumes vary under different conditions of GDP growth, specifically, embodying at different times values that approach saturation, and the experimental results approach the actual data (see Fig. 9.12) when the GDP growth is 15%. The fact, however, is that China's per capital GDP growth is 13.69%.[1]

The research indicates that several possible scenarios can be farmed using the scenario farming methods. This suggests then that predication accuracy regarding the future scenarios of the Three Gorges Dam Project shipping volume can be improved by comprehensively implementing other methods. Accordingly, changes in the shipping volumes of Chuanjiang in each scenario will be found, as will possible differences between design objectives and future scenarios of engineering circumstances.

These descriptions constitute only a small part of the work associated with the study of the shipping decisions of the Three Gorges Dam Project by means of scenario farming technologies. Considering the shipping conditions of the Three Gorges Dam Project, which in various scenarios are constituted by changing the combinations of different uncertainty factors, and conducting comprehensive evaluations and continuous iteration analyses, it is quite possible to obtain better prediction results and corresponding decision alternatives.

[1] According to the calculation of per capita GDP data in dollars from 1990 to 2014.

9.3 Specialized Method 3: Federal Modeling

Based on Sects. 9.1 and 9.2, the thinking about mega infrastructure construction management research method systems must take a great step forward by improving from partial, specialized methods to overall, integrated methods. With this as a goal, the two basic opinions discussed in Sects. 2.3.4 and 8.2 have importantly guiding significance on the completions of this task:

1. Mega infrastructure construction management activities reveal a type of complex integrity, and abstraction, descriptions, and analyses of this complex integrity are important for theoretical studies of mega infrastructure construction management. In particular, it should reflect the integrity of the issue of management complexity and control it.
2. A synthesized integration method system is an overall design aimed to solve issues related to mega infrastructure construction management method systems under the guidance of system theories. This method differs from the methods that are adopted or introduced during the studies of certain specific mega infrastructure construction management issues because this method is used at the complex integration level of mega infrastructure construction management issues.

More specifically, modeling methods created on the basis of system theories and during the studies of complex systems from different fields by domestic and overseas scholars over several decades provide great inspiration for the study of mega infrastructure construction management complex integration. However, to transform modeling thoughts into effective mega infrastructure construction management research method systems, these thoughts must be combined with and integrated into essential properties of mega infrastructure construction management to form effective tools and means to analyze and solve issues. In words, the methods must be focused on complex integration rather than on a certain specific issue.

9.3.1 Mega Infrastructure Construction Management Models

Models constitute the essential tools necessary for conducting scientific studies.

9.3.1.1 Overview of Models

A model is an important and universal concept in many fields of modern scientific technologies. Generally, it is defined as a representation of the fact. Specifically, it is the result of people abstracting components and correlations from elements of an actual issue to make the research more convenient. The reason why people substitute the facts with models is that models can help improve convenience, efficiency, and operability of the issue being studied. For example, original issues can be simplified through models, which are easier to understand and operate. Moreover, the use of models in studies can significantly lower costs.

As models become increasingly universal, their types also increase. The specific application fields of models include transportation, population, architecture, economy, and management, among others.

Several types are identified when the models are divided according to their structure:

1. Physical Models. These models refer to the enlargement or reduction of a physical item, such as images or photos of a physical item, plane models in tunnel tests, and atomic models in physics.
2. Mathematical Models. These model use numbers, mathematical symbols, and mathematical equations to describe and represent actual behaviors and characteristics (Lai and Wen 1997; Tan et al. 2005).
3. Computer Simulation Models. These models use computer programming languages and visual methods to describe, generate, and represent actual elements, relationships, and system changes.
4. Analogy Models. According to the similarity of two types of actual rules, one fact is used to represent another fact to strengthen the understanding and facilitate analyses. For instance, different color shades are used to represent landforms.
5. Theory Models. These models infer facts based on assumptions and idealizations.

The characteristics and functions vary from model to model. In comparison, though mathematical models are the most abstract, they are highly represented and generally cost less than other models. Physical models have a strong sense of reality, but they also come at a high cost. When selecting mathematical models, there are several types from which to select. Thus, it can be concluded that choices of model types depend on the nature of the issue and on the requirements of the research questions.

If the choice of a model is considered as a research result, the process to achieve this result, namely, the process of proposing, designing, establishing, demonstrating, and using this model, is called *modeling*. *Modeling is also known as model building.*

The modeling of simple management issues, such as linear management issues, procedural management issues, and management issues with relatively simple internal mechanisms, is relatively easy. However, for those problems with multiple levels, interfaces, and nonlinear interactive relationships, not only must people's behaviors at the micro level be considered, but management issues of organizing functions at the macro level must also be considered. Their modelings (model buildings) should comprehensively consider the complex integration of management issues. At this time, it is difficult for non-global, non-integrative, and non-comprehensive specific modeling methods to describe and depict this type of complicated management issue. Accordingly, this modeling of complex integration is quite important in mega infrastructure construction management theoretical research fields.

Therefore, in a general sense, the process of the modeling of complex integration in mega infrastructure construction management must be identified as should the general idea and technology route.

The several traditional ideas of the modeling of complex integration in mega infrastructure construction management require analysis, and the federal modelings of mega infrastructure constructions management from the perspective of the basic concepts, connotations, and key technologies of the modeling of complex integration required in-depth discussion.

9.3.1.2 Several Types of Modeling Ideas

In practice, people usually conduct system decomposition, modeling, and integration on mega infrastructure construction management issues according to the topics, system levels, time workflows, and management scenarios, from which are formed four types of traditional overall modeling ideas of mega infrastructure construction management, namely, thematic modeling, hierarchical modeling, process-oriented modeling, and scenario modeling (Banuls et al. 2013; Willemsen 2000; Beltratti et al. 1999).

1. Thematic Modeling
   Thematic modeling refers to the divisions of integrated issues in mega infrastructure construction management into several themes. For example, the Hong Kong-Zhuhai-Macao Bridge decision issues are divided into dozens of decision themes whereby every theme has clear ideas and distinct interfaces. The modeling process is relatively independent from its styles, and its modeling can be based on different themes and applied to various studies. Several themes can be combined into or can revert to a greater management issue, and combinations of several modelings can be regarded, to some extent, as the modeling of this management issue. However, it cannot be regarded as a modeling of complex integration in mega infrastructure construction management as there is no significant.
2. Hierarchical Modeling
   Hierarchical modeling suggests that the integration of mega infrastructure construction management is considered a systematic integration structure that has multiple levels and is resoluble and that the analyses and modeling of its relatively simple substructures can be easily conducted. For instance, the integration of a certain mega infrastructure construction management can be considered a structured integration management that is divided into a three-level system structure: infrastructure, management objects, and goal controls. Accordingly, the contents of each level are presented in Fig. 9.13 (Sheng et al. 2009).

   Hierarchical modeling ideas are reductionist-oriented modeling thoughts. The overall structures built upon these ideas describe close vertical correlations and lateral independent features of mega infrastructure construction management integration. However, the lateral correlations can be artificially separated.

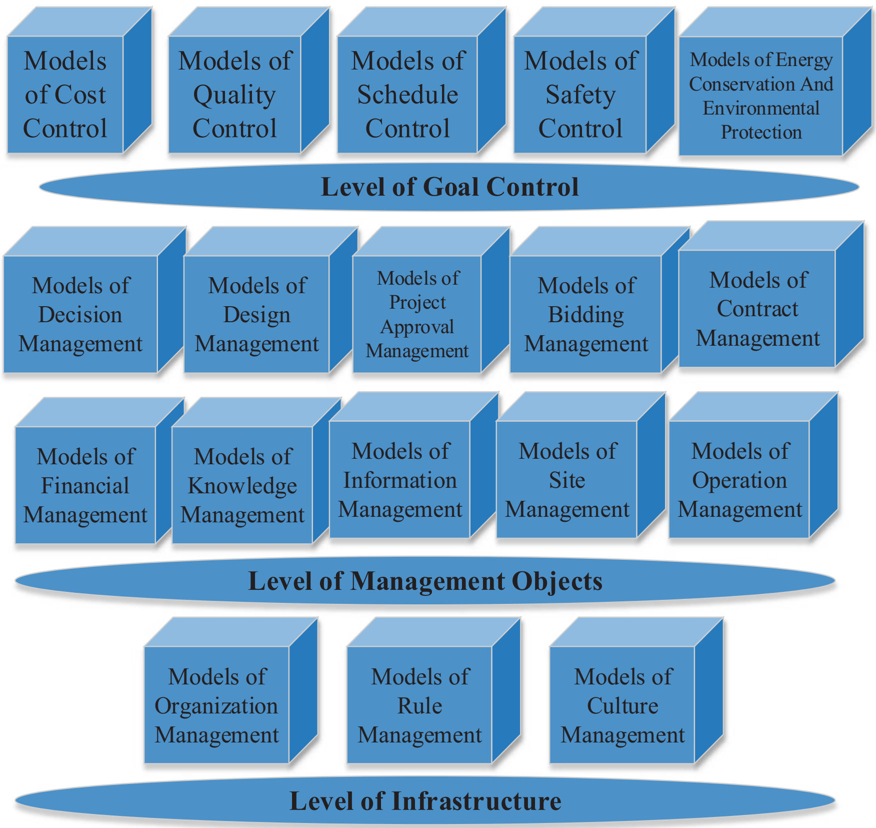

Fig. 9.13 Hierarchical modeling ideas

Furthermore, the modeling process does not give sufficient attention to the management subjects' behaviors and environments, and the overall modeling combinations and integrations of the later period are faced with several problems.

3. Process-oriented Modeling
   Process-oriented modeling is an integrated modeling system that is structured according to mega infrastructure construction decisions, designs, constructions, operations, and management activity sequences in the general sense and that contains life cycle major management activities of mega infrastructure construction management. Due to different management issues and objects occurring in different management periods, the management subjects and processes are self-constructed. However, mega infrastructure construction management itself is an organic whole, and as such, there are relatively strong correlations between management activities during various life cycles. Generally, the former management activities influence the latter management activities, whereas the latter activities

are usually a type of continuation, succession, development, and realization of the former activities. To avoid damaging the integrity of mega infrastructure construction management activity modelings, there must be a focus on the relations between connecting and transmitting, between including and being included, between the principal and the subordinate, between casual relationships, and between descriptions and abstractions of the integration connotations among management activities for each period during the life cycle of mega infrastructure construction management.

Compared with hierarchical modeling, process-oriented modeling is able to better connect management activities and management issues that appear during different periods of the life cycle. Thus, management issues can collect and integrate through various logical relations. However, the hierarchy of management systems is seldom considered during process-oriented modeling discussions.

Despite the integration of thematic, hierarchical, and process-oriented modeling, the end result is a relatively complete management modeling system of mega infrastructure construction. Its specific contents are presented in Fig. 9.14 (Sheng et al. 2009). However, these types of modeling thoughts and modeling systems are not strong enough to support the descriptive abilities of mega infrastructure construction management's complex integrations, because they have

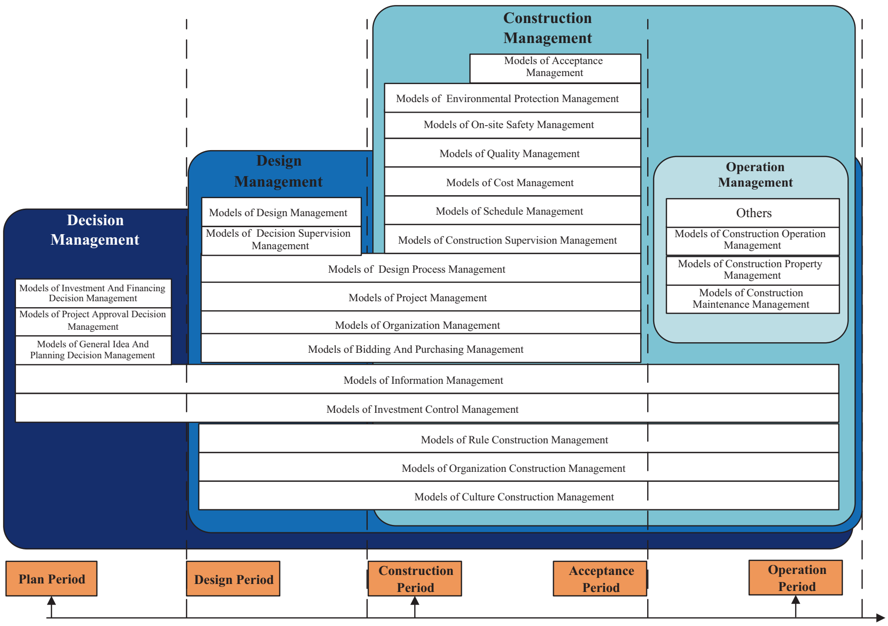

Fig. 9.14 Process-oriented modeling ideas

not introduced adaptability making complexity, the emergence from microscale to macroscale, the evolution of whole system behaviors, and other complexities to the construction of the whole modeling system.

4. Scenario Modeling
   Scenario modeling refers to the modeling of mega infrastructure construction management issues centered on mega infrastructure construction management scenario elements and element structures. As such, scenario modeling can build the model according to the occurrences of mega infrastructure construction management issues and the internal logics and rules of development through the use of scenario languages and modeling notations, including when, where, who, what, why, and how it will be (Wang et al. 2004; Strang and Linnhoff-Popien 2004; Zhong et al. 2012).

To be more specific, certain contents must be described and abstracted. These include:

1. The occurrences of mega infrastructure construction management issues, time control, time requirements, and time dynamic changes of development, as well as the occurrences of issues, their spatial distribution, and spatial influential attributes
2. The mega infrastructure construction management assignments, which should focus on illustrating the studied management issues that belong to specific management assignments and relationships between management issues and assignments
3. The statistical information, psychologies, behaviors, habits, goals, preferences, and responsibilities of the mega infrastructure construction management individuals, such as construction subjects, contractor managers, suppliers in charge, and public and expert consultants, which should focus on finding the relationships among mega infrastructure construction management individuals, management issues, and management assignments
4. The goals, benefits, functions, organizational structures, organizational behaviors, and other information regarding the mega infrastructure construction management organizations, such as governments, investors, consulting organizations, proprietors, designer organizations, investigative organizations, contractors, suppliers, and supervision organizations, which should focus on describing and abstracting the relationships among management issues, assignments, individuals, and organizations
5. The contents, predictions, conflicts, and constraints of mega infrastructure construction management issues, which should focus on describing and abstracting the specific time and space background and the relationships between management issues and assignment sequences and between individual management behaviors and organizational structures
6. The occurrences of mega infrastructure construction management and the natural, social, marketing, economic, political, and cultural circumstances in which they develop with the aim to analyze interactions between mega infrastructure

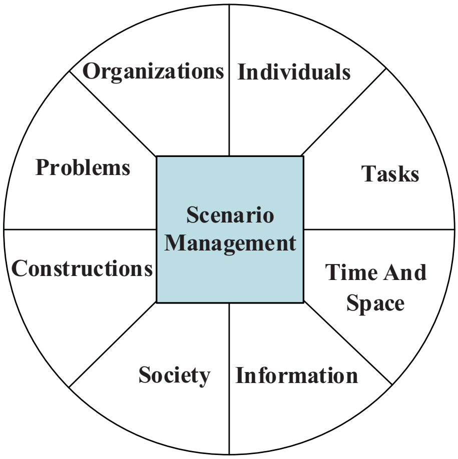

Fig. 9.15 Scenario modeling thoughts

construction management circumstances and management issues, especially practicability, necessity, and urgency of mega infrastructure construction social economic benefits

7. The physical system of mega infrastructure construction management, including construction systems, construction equipment, construction natural environment, and construction formation process and rules whereby interactions between construction assignments and physical constructions should be sorted out
8. Mega infrastructure construction management information, which should focus on interactions between management information features (abundance, accuracy, promptness, transmission patterns, sharing patterns, and tools) and management issues and should analyze the management issue occurrences and development regularities in the event of asymmetric, incomplete, and complete information (see Figs. 9.15 and 9.16)

Scenario modeling should focus on descriptions and abstractions of scenario elements included in models and on explanations as to how to build scenario models. Most mega infrastructure construction complex management issues are described and abstracted based on construction management scenario elements, i.e., time and space, assignments, individuals, organizations, issues, constructions, and society, which is beneficial for the integration of modeling thoughts for mega infrastructure construction management modelers and for the collection of data and the integration of later models.

Compared with thematic, hierarchical, and process-oriented modeling, scenario modeling thoughts are better at expressing the influences of time and space features, construction environments, social environments, individual behaviors, organizational structures, and information features of mega infrastructure construction management issue occurrences and their development. In addition, scenario modeling

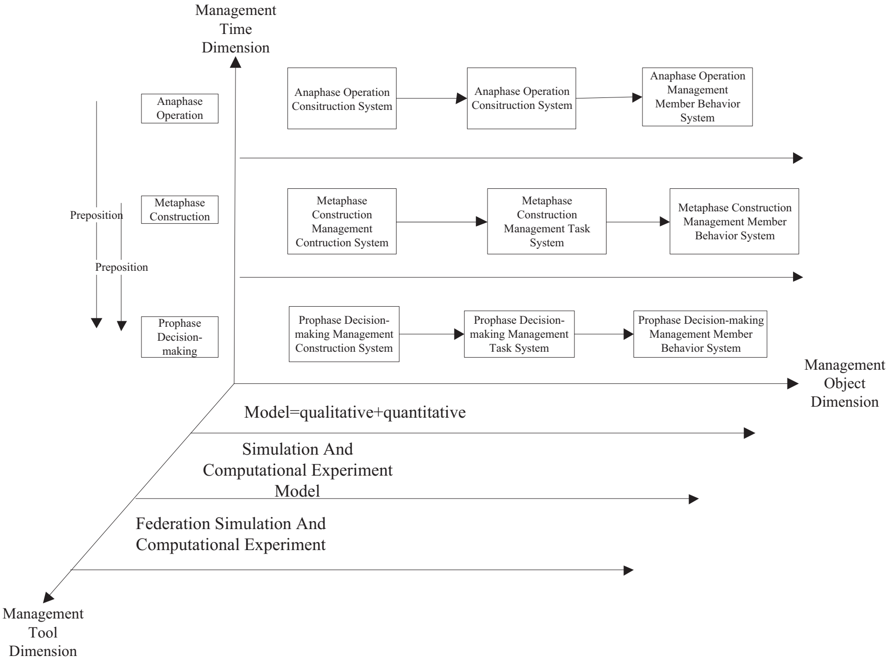

Fig. 9.16 General idea of federation modeling for mega infrastructure construction management

thought with respect to mega infrastructure construction management issues is a type of higher level abstraction and modeling that abandons specific management issues because it is concerned with the description and abstraction of general and fundamental elements, element structures, and environments that exhibit higher model universality and modeling guidance. Any specific mega infrastructure construction management issue can be described and abstracted under the framework of mega infrastructure construction management scenario modeling, and as such, it is capable of providing relatively good descriptions of the adaptability of individuals and organizations to mega infrastructure construction management issues, the occurrences of the issue scenario dependency on development, and future uncertainties of management issues. This suggests that scenario modeling thoughts have better descriptive capacities regarding management issue complexity and that these thoughts correspond to man's imagery thinking habits, a finding that is beneficial to communications and cooperation among the different modelers.

However, there are shortcomings in mega infrastructure construction management issue modeling thoughts that are based on the scenarios. For example, it is easy for excessive modeling abstractions to separate themselves from specific issues of mega infrastructure construction; scenario modelings have not provided satisfying descriptions of hierarchical relationships among the various systems; scenario modelings have not provided an explanation of management issues' granular control; and not all management issues require management scenario studies.

9.3.1.3 Federal Modeling

Based on the discussions provided herein regarding the complex overall modeling thoughts of mega infrastructure construction management, it is concluded that the difficulties in the complex overall model building (or modeling) of mega infrastructure construction management issues lie in how to abstract and demonstrate, fully and completely, the complexity attribute, the attribute relationship, the complexity of human behaviors and construction scenarios, and the scenario evolution paths of mega infrastructure construction management issues. The solution must be a comprehensive integrated modeling process that is comprised of several characteristics:

1. Considers autonomy and adaptability of subjects' behaviors during mega infrastructure construction management activities
2. Considers the features of multi-level, multi-node, and complex overall structures during mega infrastructure construction management activities
3. Considers micro-mechanisms and how micro-mechanisms emerge into macro phenomena during management activities
4. Considers complex changes in management activity circumstances and how these changes influence management subjects' behaviors and management activities
5. Considers questions about how management issues, behaviors, and phenomena evolve
6. Considers the complex integrity of management issues and integrates integrity and complexity

In addition, according to the principles mentioned in Sect. 8.2, this modeling process fully expresses core thoughts and principles of comprehensive integrations. Certain means and tools, such as multi-type, multi-scale (Weinan 2011; Weinan and Engquist 2003), and multi-level modeling methods and modeling systems, can be used to describe the complexity of mega infrastructure construction management and to assist subjects to form corresponding abilities of coping with management complexity.

This means that the result of mega infrastructure construction management modeling must be a system that is composed of multiple modeling types. Thus, for a specific model, it is the abstract of a certain part or a certain issue of mega infrastructure construction management activities that has relatively independent functions. If applied, certain parts of the management issues can be described, analyzed, and designed, the revolutions of a certain issue can be designed, and the predictions of a certain management environmental scenario can be analyzed. However, such a model is only the description of a certain part of the entire set of mega infrastructure construction management activities. Accordingly, this model must still connect with other models in the modeling system to form multi-level network structures and function as a complete representation of mega infrastructure construction management's complexity integrity. Accordingly, relationships between models are formed based on several models through a series of rules and contracts.

Individual models in this modeling system are relatively independent, and there are features of several association rules and contract relationships among the various models that are similar to the federal form in national governance theories. Consequently, *this type of modeling process is called federal modeling of mega infrastructure construction management, and the corresponding modeling systems are referred to as federal modeling systems of mega infrastructure construction management.* With respect to these titles, the term federal must be clarified.

1. The integrity of mega infrastructure construction management systems can be regarded as a complex network that is composed organically of a series of federal units. Each model in the federal modeling system is relatively independent and highly autonomous. Based on certain rules and contracts, models are connected to each other and maintain the transmission and relationships between data, information, and functions in various forms, and the complex integrity of mega infrastructure construction management is reflected as a whole.
2. Individuals or parts of models in federal modeling systems demonstrate top-down reductionism in the modeling process, whereas the integrity of correlative forms among various models, which is built on certain rules and contracts, demonstrate down-top holism in the modeling process. Finally, the systematic theories based on reductionism and holism reveal the complex integrity of mega infrastructure construction management.
3. According to Sect. 2.4.3, the federation is not only the federation between physical elements of management systems and functional elements of management activities, but it also refers to the federation between various element properties and property relationships of management systems and between management subsystems of different constructions, different time-space scales, different levels and dimensions, and other management complexities.
4. The federation also includes the integrations and combinations of various means, tools, and methods among the several subjects.

In conclusion, federal modeling is a process that puts forward, designs, establishes, and recognizes multi-level, multidimension, and multi-scale modeling systems of mega infrastructure construction management complex integrity based on several types of models, including qualitative, quantitative, regular, computer simulation, experimental, procedural, etc., through several modeling technical routes. This system's function is to describe and reveal mega infrastructure construction management's complex phenomena, analyze the inner rules, and guide the implementation of the practical activities of mega infrastructure construction management. Accordingly, federal modeling is an effective tool and method for the study of mega infrastructure construction management complex integrity.

9.3.1.4 Fundamental Connotations of Federal Modeling

Through interpretations and explanations presented herein, the fundamental connotations of federal modeling are determined and generalized:

1. Fitting into the Category of Complex System Modeling
   Mega infrastructure construction management is an open but uncertain complex system where humans, items, and environments are highly coupled. Thus, it requires complex system models to describe its systematic complexity. However, federal modeling conducts the model building for mega infrastructure construction management issues in relatively supportive environments through qualitative and quantitative methods, computer simulations, and computer experiments combined with the experiences and knowledge of experts from several fields with the aim of analyzing, exploring, and predicting the uncertainty, adaptability, and emergent and evolutionary rules of mega infrastructure construction management. It also includes the modelings of relatively simple procedural questions, deterministic questions, and structured questions. Accordingly, federal modeling of mega infrastructure construction management fits into the category of complex system modeling.
2. Upholding the Thinking of Comprehensive Integration
   Mega infrastructure construction management must accumulate management personnel and technical talents, integrate various resources, and apply methodologies of comprehensive integration to efficiently manage its inherent complexity. Similarly, as a construction, federal modeling of mega infrastructure construction management is a modeling organization pattern that should uphold the thinking of comprehensive integration and coordinate with modelers to promote participants' collaborations of tasks and to fully stimulate collective intelligence of modeling. Such a pattern not only divides and arranges modeling assignments according to modelers' specialties and mutually independent but dependent federal relationships among management subsystems of various levels and different resolutions, but it can also improve the modelers' recognition, understanding, and implementation of complex system modeling thoughts that combine top-down reductionism and down-top holism, through more convenient information exchange and knowledge sharing to guarantee the completion of various tasks of complex overall modeling in mega infrastructure construction management.
3. Combinations of Holism and Reductionism
   Although a few models may be able to adapt to a simple construction, mega infrastructure construction management modeling requires comprehensive integrations of modeling systems of various types and functions. The purpose of federal modeling of mega infrastructure construction management is to fully reveal dialectical relationships of the whole and the local parts and the emergent relationships between the different levels through combinations of holism and reductionism. This not only attaches importance to the overall phenomena at macro levels but also emphasizes the operation mechanism at the meso levels and the individual behaviors at the micro levels. In addition, the federal modeling of mega infrastructure construction management not only requires top-down systematic stratification and decomposition, which decomposes original construction systems into relatively simple subsystem models that are easier to use

in studies, but it must also conduct down-top integrations and find relationships between the elements of complex systems. This modeling process combines top-down systematic decompositions and down-top overall integrations together with several iterations of the process. Furthermore, it is a gradual modeling process composed of multiple stages.

4. Human-Oriented Man-Machine Modeling Methods
   Federal modeling of mega infrastructure construction management is not only a process for mutual discussions, idea exchanges, assignment coordination, and knowledge sharing, but it is also a human-oriented working process that combines humans and computers. As such, it requires a series of organization and management methods of federal modeling and the support of federal simulation tools, techniques, and methods. Therefore, computer platforms of federal modeling and federal calculation experiments that can fully utilize and exploit the computer's advantages of data storage, calculation, communication, and visualization must be constructed. However, during this process, the advantages of man's leading roles, man's innovation abilities, and man's understandings of nonstructural complexity of mega infrastructure construction management should also be emphasized.

   Specifically, federal modeling of mega infrastructure construction management must create a supportive environment for federal modeling computers that is composed of construction information models, management assignment information models, man's behavior models, corresponding management systems, and distributive simulation modeling frameworks. Furthermore, the environment should provide support for the decisions and analyses of various management issues and for the construction, integration, tests, and operation management of heterogeneous models in various fields and for various management issues.

5. Systematic Interconnectedness Functioning as a Basic Premise
   During the process of the federal modeling of mega infrastructure construction management, attention should be directed toward the modeling of different thematic systems, especially the modeling of dynamic interactive relationships between various subsystems. This means that the federal modeling of mega infrastructure construction management must describe and determine the rules about interactive relationships of materials, abilities, and information between subsystems. In conclusion, systematic interconnectedness is a basic premise of the federal modeling of mega infrastructure construction management. Consequently, it is necessary to intensively study the influence of interconnectedness between various mega infrastructure construction management subsystems with respect to structures, functions, and complexity characteristics of mega infrastructure construction management systems.

9.3.2 Main Contents of Federation Modeling for Mega Infrastructure Construction Management

9.3.2.1 Basic Concepts

Based on the information and discussions presented herein, a definition of federation modeling can be formed. *Federation modeling of mega infrastructure construction management is a model approach for exploring and researching the complex integrity of mega infrastructure construction management. It is the global idea and principle behind the understanding, degrading, and solving of complex mega infrastructure construction management issues. The result of federation modeling for mega infrastructure construction management is the development of federation models for mega infrastructure construction management.*

As a comprehensive modeling approach for mega infrastructure construction management, the federation modeling of mega infrastructure construction, which is independent of both specific management issues and the detailed modeling properties and techniques of management issues, displays a universal scheme. The scope of federation modeling for mega infrastructure construction management also falls into the description and abstraction category of mega infrastructure construction management issues and activities. Because it distinctly possesses the characteristics of mega infrastructure construction management, it is distinguished from the modeling of general infrastructure construction management, society management, and economy management.

Adhering to comprehensive integration theory and integrating the knowledge of multiple fields with the modeling of multiple methods and models of multiple types, federation modeling for mega infrastructure construction management strives to build a modeling framework or system that is capable of accommodating, integrating, and linking more specific management activities and modeling techniques with the wisdom of model builders. Accordingly, it covers multiple types of mega infrastructure construction management issues without overstepping the basic scope and border of mega infrastructure construction management.

Methods of this type can be applied to the modeling of simple infrastructure construction management issues, i.e., management issues that are small in scale, linearized, programmed, or low in certainty. However, such methods are generally adopted to model highly complex issues in mega infrastructure construction management.

This requires understanding that although federation modeling for mega infrastructure construction management is a modeling system, it is not a large model concept because a large model is still a model, and mega infrastructure construction management can hardly apply only one “super model” to describe and abstract all management activities and issues. Further, the models in the model base are relatively independent and loosely connected without incident relations or presuppositions and functions.

Table 9.5 Application conditions for federation modeling in mega infrastructure construction management

Modeling method	Issues to solve	System level	Methodology	Modeling difficulty
Federation modeling	Systematic complexity	Macro; holistic	Meta-synthesis	High level
Nonfederation modeling	General systematicness	Micro; partial; local	Modulation; processing; standardization;	Low level

9.3.2.2 Basic Principles

1. Complexity Principle
   Federation modeling does not need to be applied to all issues regarding mega infrastructure construction management. Instead, it mainly addresses the modeling of management issues of complex integrity, especially the modeling of the global and general mega infrastructure construction management issues. Therefore, structuralized models, instead of federated models, can be established for the local, micro, and partial programmed management issues based on modular, processing, and standardization thoughts, as presented in Table 9.5.
2. Integration Principles of Self-organization and Hetero-organization
   The formation of federation modeling in mega infrastructure construction management involves both the self-organization of the group experiences, knowledge, and abilities of the modeling bodies and the hetero-organization of the purposes, procedures, rules, and systems of united modeling. Thus, during the process of federation modeling, the characteristics that global planning coexists with local autonomy and general stability accompanies partial wavering are illustrated. Therefore, the mechanism to ensure global planning and local autonomy should be established and improved during the early stages of federation modeling.
3. Iterative Approximation Principle
   The federation modeling for mega infrastructure construction management is a loop-clocked iterative approximate process of continuous trials and errors and inspections and feedbacks that is usually filled with uncertainty and, in certain circumstances, the risk of going out of control. Therefore, during the federation modeling of mega infrastructure construction management, the complexity of the quantitative accumulation of federation modeling should be fully recognized, and attention should be focused on the control of the stopping system of the iterative approximation, for example, the level of model abstraction, size control, comprehensive balancing, and model resolution control. The justification for this is that blindly emphasizing the modeling of high-resolution or high levels of abstraction will result in actions that are contrary to the original intentions of federation modeling to recognize and express the complex integrity of mega

infrastructure construction management issues. It is safe to balance the needs, techniques, and costs of modeling to achieve the providential modeling ability cultivated during the process of modeling based on certain prospective principles of modeling and according to the specific requirements of mega infrastructure construction practices.

4. The Principle of Distribution
   Because mega infrastructure construction issues are multi-level, multidimensional, and multi-scaled, the models of management issues should be constructed based on the specific person, case, time, and place, which means that mega infrastructure construction-federated models are necessarily temporally distributed. This suggests that from the perspective of the single modeling individual scenario, the construction of its models is relatively free of temporal constraints and the influence of modeling knowledge and modeling heterogeneous thinking, whereas from the perspective of the modeling group, every model-constructor must advance in a distributed way and under unified modeling targets, principles, and environments.
5. The Principle of Consistency
   Under the majority of circumstances, federation modeling in mega infrastructure construction management displays a multi-person and distributed collaborative process. To improve the effectiveness and quality of federation modeling for mega infrastructure construction management, the consistency among modeling objectives, principles, and environments should be maintained under the unified top-level design.

The consistency of federation modeling for mega infrastructure construction management refers not to the uniqueness of the modeling purpose but to the complementarity of modeling functions, which means that models of different functions are complementary in function through combination, after which an additional function emerges. For the consistency of the mega infrastructure construction management federation modeling principle, there is no requirement for modelers to build a model in accordance with unified modeling knowledge, theory, language, and tools. Rather, it only requires an agreement on the consistency of the modeling object, target, and interface. Consistency with respect to the modeling environment refers to the consistency observed among the computer software engineering environment, conditions, and platform upon which the modeling is based.

9.3.2.3 Basic Requirements

Different from general infrastructure construction management, mega infrastructure construction management possesses the federated characteristic of multi-subject autonomy. Therefore, to fully demonstrate this characteristic, it is necessary to integrate multiple modeling ideas, methods, and techniques. A qualified mega infrastructure construction management federation modeling process should adhere to the several basic requirements:

1. Integrated Modeling
   The mega infrastructure construction management system is complex, and the target of federation modeling should be an integrated one. This requires that the final results be a whole set of an interrelated modeling system. To achieve this requirement, modelers should focus on and maintain the integrity of the system throughout the process, without reckless decomposition, stratification, and reduction of the integrity of management issues during the process of modeling and without the holistic modeling of the system relying on the bottom-up comprehensive systematic integration after the decomposition of system. This is because without the decomposition of integrity, it will remain difficult to achieve an effective comprehensive integration.
2. Autonomous Modeling
   Mega infrastructure construction management is a complex system composed of a large number of local autonomous federated management activities. This means that the federation modeling of mega infrastructure construction management should fully consider the relationship, the rights, and the characteristics of the functional structure between the parts and the whole of the system. Specifically, the modeler should provide detailed descriptions and abstractions of the autonomous characteristics of the mega infrastructure construction management system, regard every federal member as a unit of autonomy and rights, and focus on describing the internal elements, structure, autonomous attributes, and autonomous behaviors of the federal members and on describing the autonomous relationship between the federate and the overall system, thereby clarifying the autonomous scope, boundaries, and environment of the federal members. Furthermore, it is important to understand that autonomous modeling requires that different modelers be internally autonomous and that no extreme strict regulation be set on the modeling methods, techniques, and language with respect to modelers. Generally, only the basic model communication rules and interface specifications can be set; thus, it is encouraged to fully exploit the modeling autonomy under a unified framework.
3. Distributed Modeling
   To embody the distributed characteristics of mega infrastructure construction management activities, mega infrastructure construction management federation modeling should not only focus on the description and abstraction of traditional serial and parallel logic relationships in mega infrastructure construction management activities but also pay close attention to the description and abstraction of the distributed network logical relationship. It is further emphasized that the logic of the allocation, coordination, and cooperation of mega infrastructure construction management modeling tasks can be a distributed processing method, which means that under the overall thinking, extremely complex mega infrastructure construction management modeling tasks should, to the greatest extent possible, be allocated to the modeling individuals or organizations that are most capable of managing them.

4. Hierarchical Modeling
   The hierarchical characteristics of mega infrastructure construction management federation modeling are manifested in two ways. First, the modeling fully demonstrates a variety of hierarchical characteristics of mega infrastructure construction management activities, for example, to refine, supplement, describe, and abstract the hierarchical process, the way of evolution, and the changes of the relevant factors of the framework model and detailed model. Second, to constantly improve the quality of the modeling, the modeler should continuously modify and improve the division of different model stages and the choice of model accuracy with respect to mega infrastructure construction management, the abstract principles of the hierarchical relationship, and the linking methods of different models of different stages.
5. Adaptive Modeling
   Every federated subject of mega infrastructure construction management possesses a certain ability to self-learn, self-adapt, and self-improve. While modeling, it is important to describe and abstract the main psychological, behavioral, and value orientations of the mega infrastructure construction management activities as the key features of system adaptability. For example, while modeling the sequential subject behavior of mega infrastructure construction management, description and abstraction of adaptive traits such as learning and heredity, the mutation of sequential subjects should be increased. During the process of multi-model integration in a federation modeling system, the modeling theory, knowledge, methods, and techniques of modelers will change dynamically, or an adaptive process of continuous communication, learning, and coordination will occur among modelers during the building of the mega infrastructure construction models and modeling itself.

Accordingly, it is evident that the basic requirements of federation modeling for mega infrastructure construction management are identical to the basic concept and principle of mega infrastructure construction management theories presented in Chapters 5 and 6 of this book, which is not accidental. Rather, to a large extent, it is consistent with the theoretical logic and logical thinking regarding the model. Because the essence of the model is a representative of reality, i.e., a modeling object, it is the exact and comprehensive representation of the reality in another discourse system. Therefore, the modeling process establishes a mapping relationship between the original reality and its representative, resulting in the representative becoming the image of the reality. Although the two are rarely identical, a qualified model should, in the process of becoming an image, maintain as much of the original nature as possible. The basic concepts and principles given in Chapters 5 and 6 are the most basic description of mega infrastructure construction management federation modeling rules and guidelines, and therefore, they should definitely act as intrinsic genes to be inherited and become the basic requirements of modeling during the process of federation modeling for mega infrastructure construction management.

9.3.2.4 Basic Objectives

The basic objectives of federation modeling for mega infrastructure construction management are divided into three levels, namely, the federation of the model, system, and management, among which the federation of the model is the foundation. Then, under the guidance of the federated rules of modeling, an integration of the system, which is distributed, heterogeneous, mature, and validated, is provided by the federation of the system to create a federation modeling environment and simulation environment for supporting all types of management issues:

1. The Federation of the Model
   The federation of the model is the integration of every management model to build a multi-level, scalable, and dynamic model system. Such a model system not only describes the macro, meso, and micro issues of mega infrastructure construction management, but it also provides descriptions of varied types of mega infrastructure construction issues through qualitative and quantitative analysis and experimental simulation and simulates different types of management issues through the simulation of scalable resolution. To achieve the federation of the mega infrastructure construction model, an environment that can support the coordination of a heterogeneous model should be developed to enable different types of modelers to realize all types of convenient, flexible, and integrated model construction under the overall framework of the mega infrastructure construction management federation modeling.
2. The Federation of the System
   The federation of the system provides a distributed, heterogeneous, mature, and validated integration of the system that is designed to align with the federal environment. The basic contents include the federation and integration of the engineering construction system, the engineering task system, and the engineering behavior system. The engineering construction system primarily focuses on the abstraction of the engineering physical system, whereas the engineering task system is the abstraction of all types of construction management tasks. The engineering behavior system is the abstraction of the behavior of all participating subjects in construction management activities and behavior interactions. Integrating these distributed, heterogeneous, mature, and verified systems is an important task for mega infrastructure construction management federation modeling. In addition, the support from the HLA framework of heterogeneously distributed simulation is required, and the combination of various types of subsystems calls for the HLA framework.
3. The Federation of Management
   The targeted function of the federation of management is the federation of the comprehensive management of engineering construction, tasks, and behaviors. All construction elements are, to the greatest degree possible, digitized and informationalized. Thus, a federation modeling environment and simulation environment sufficient to support all types of management issues are created through the federation of the model and the system. Moreover, these environments must

enable the management, modeling, and technical personnel to exchange information and coordinate tasks under a unified modeling and simulation support environment. Such a support environment provides management personnel with unified, accurate, and complete data support, enables model building and simulations of systems, and provides intelligent decision-making and support for all types of management issues, including design, construction, and operation.

9.3.3 The Implementation of Federation Modeling for Mega Infrastructure Construction Management

9.3.3.1 General Premise

Three dimensions can be adopted to discuss the general premise behind federation modeling for mega infrastructure construction: time, objects, and tools. From the perspective of the dimension of time, mega infrastructure construction management issues are distributed in prophase decision-making, metaphase construction, and anaphase operation management periods. In the time dimension, these three stages are both separated and correlated, and the management objects and subjects of the different stages are distinct from each other. Therefore, deviation and discontinuity must not appear in the connection of prophase and anaphase. Based on this, system federation in different stages of mega infrastructure construction management should first be well regarded in federation modeling as this can build a model system structure capable of supporting the entire staff, process, and information of mega infrastructure construction management through information technology, i.e., computer technology and network technology.

From the perspective of the management objective dimension, management objects in any management stage of mega infrastructure construction involve an engineering construction system, task system, and member behavior system. The engineering construction system refers to the mega infrastructure construction hardware system, including the physical elements, spatial layout, geometric structure, appearance, function, and environment of the project. The task system involves the objectives, resources, functions, processes, and information collection of mega infrastructure construction management tasks, including the design, construction, and operation of the management tasks of various stages. The member behavior system refers to the collection of management subject behavior, behavior properties, and behavior interaction relationships. When in the same stage, these three systems serve as a whole that constitutes the federation system. Accordingly, this system can be characterized by the construction information model, task information model, and member behavior information model. The three systems in different stages also possess federation relationships and serve as truncations at different time periods within the system.

From the perspective of management tools, the available tools for mega infrastructure construction management modeling include the qualitative model, quantitative model, and simulation or computational experiment model. Mega infrastructure construction management federation modeling simulation adopts federal simulation and computational experiment tools and methods based on qualitative and quantitative models. Therefore, advanced methods and techniques, such as computer-aided design methods, virtual designs, and construction navigation methods, as well as distributed system modeling and simulation technology should be applied in mega infrastructure construction management federation modeling. Through the development of mega infrastructure construction information modeling as well as the construction task information model and the member building information modeling and the integration of these models into a distributed heterogeneous system simulation modeling HLA framework, the digitization, informatization, and intellectualization levels of mega infrastructure construction management are improved, and the mega infrastructure construction federation simulation and computational experiments are realized.

In addition, the complex system modeling theory and its methods serve as a reference for mega infrastructure construction management federation modeling, and thus, full consideration should be given to the human factors in the mega infrastructure construction management process, especially with respect to the challenges that result from nonrational behaviors and uncertain factors of the design, construction, and operation of mega infrastructure construction.

In specific modeling operations, multi-subject modeling technology should be applied to build a mega infrastructure construction management artificial society model with which the corresponding database integrates to complete the mega infrastructure construction artificial social information model. In this artificial information model, researchers and managers are free to define the influence of the value conflict, game interests, and nonrational behaviors toward the mega infrastructure construction decision-making management path and its efficiency and quality. Studies regarding the formation, evolution, and governance of mega infrastructure construction decision-making risks are conducted based on this artificial society model. Furthermore, mega infrastructure construction management federation modeling requires the strength and wisdom of experts and scholars from a variety of fields and from on-site technical staff as well as the full use of systems, models, and data regarding the existing mega infrastructure construction management issues to create a federation environment for mega infrastructure construction complex system management issues and to overcome the problems regarding the lack of support in mega infrastructure construction management federation modeling and lack of simulations, data, information, models, and systems required for computational experiments.

9.3.3.2 Basic Technical Framework

The supreme goal of mega infrastructure construction management federation modeling is the federation of management, whose implementation is based on the federation of the system and model. There are two critical tasks of the mega infrastructure construction management federation of model:

1. The Abstraction and Modeling of the Mega Infrastructure Construction Management Federate
   Federates are mainly composed of management activities and sub-management activities that may be locally autonomous but subject to overall coordination. Such management activities include the participating subjects and organizations; the tasks, objectives, and processes associated with the activities; and the space and time information, social environment, and engineering environment management activities.
2. The Abstraction and Modeling of the Mega Infrastructure Construction Management Federation Relationship
   This refers to the specific content, scope, and managing rules of local autonomy and global coordination among every federate. In addition to local autonomy and global coordination, the logical relations at the system level and the whole life cycle engineering dimension of mega infrastructure construction management can be described and abstracted as part of the federation relationship.

Specifically, the mega infrastructure construction management federation model framework assumes the cognitive framework of mega infrastructure construction management activities as the meta-model and considers its sub-activities as independent federates to establish every federate model. Through the integration of the qualitative and quantitative models and the computational experiment model, such a federate construction method can gradually refine the core scenario elements, such as individuals, organizations, task, time, space, information, engineering environment, and management issues, all of which are elements of management activity. Finally, through assembly and combination, a relatively complete mega infrastructure construction management federation model can be realized. Its specific content and logical relations are presented in Fig. 9.17.

Figure 9.17 illustrates that the basic framework of the constructing mega infrastructure construction management federation model includes the reuse and connection of cognitive models of general management as well as the continuous refinement of mega infrastructure construction management scenario elements. It is important that detailed descriptions and abstractions of the communication interface and interaction rules among federates be incorporated to realize a relatively complete mega infrastructure construction management federation model.

With respect to the general management cognitive model, if mega infrastructure construction management activities are abstracted to the level of general engineering, the content of the cognitive framework should include management subject, decision-making management, management scenario, and the relationships among them, which should possess the characteristics of mega infrastructure construction management. For example, the management subject in the cognitive framework of mega infrastructure construction management can refer to the government, construction management agencies, contractors, suppliers, research institutes, and consultants. The decision-making management of the framework is more complex, however; thus, the factors to be considered may relate to environmental protection, national security, and social economic development, among others that are distinct

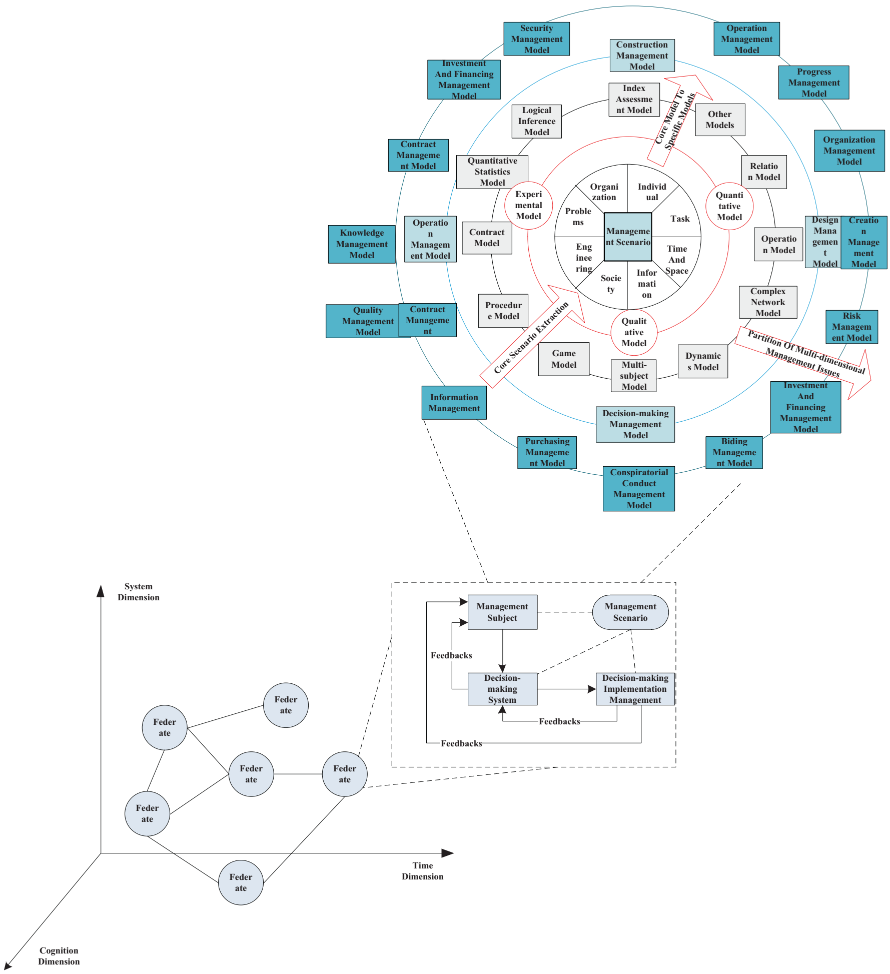

Fig. 9.17 Mega infrastructure construction management federation model framework diagram

from the general construction management. Furthermore, the activities are more complex than those related to general management.

The management activities in the cognitive framework of mega infrastructure construction management may include one management activity or a combination of multiple management activities. The specific number of management activities is decided by the cognitive abilities of the people involved in the mega infrastructure construction management activities. When the cognitive abilities are relatively high, mega infrastructure construction management activities can be considered only a management activity. However, when the cognitive particle size is small, mega infrastructure construction management activities can be a combination of a series of sub-management activities, every one of which can be equivalent to a general management activity.

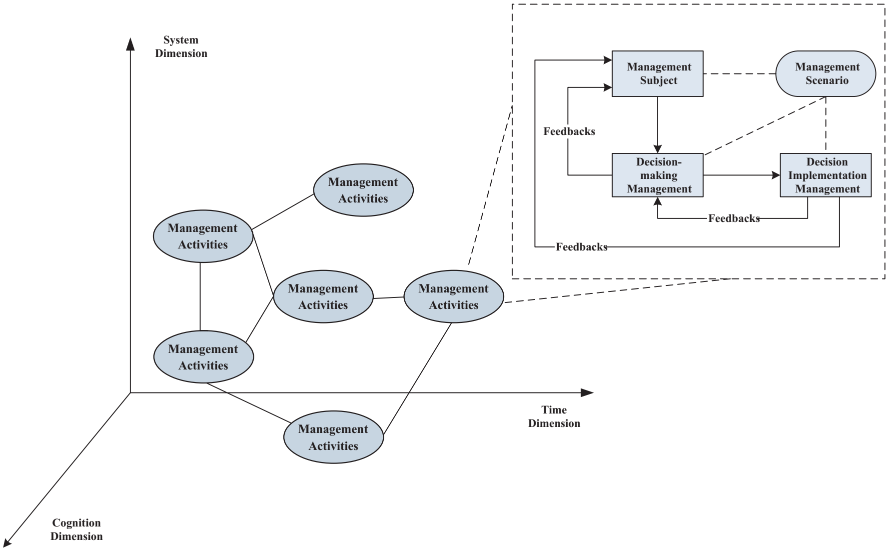

Fig. 9.18 Mega infrastructure construction management activity cognition framework

Based on these concepts, the cognitive framework of mega infrastructure construction management activities can be organized as depicted in Fig. 9.18. As such, it is a federal system that is composed of a series of relatively independent sub-management activities, and it is established based on the foundation of mega infrastructure construction management with a series of sub-management activities forming the mega infrastructure construction management system. The time dimension in this system can be used to describe the information of the mega infrastructure construction management multistage life cycle management scenario; the system dimension can describe the information of the mega infrastructure construction management multi-scale system management scenario; and the cognitive dimension can describe the mega infrastructure construction management cognitive hierarchical management scenario information.

In addition, the construction of the technical framework of the mega infrastructure construction management federation model includes the development of a federation technical support framework and task collaboration framework, whose natures are prearranged based on the same rules, requirements, and procedures that are either paper-based or can be solidified through a set of information system platforms. As the complexity of mega infrastructure construction management increases, it is important and necessary to make full use of modern information technology to control, guide, and solidify the mega infrastructure construction management federation model development process.

9.3.3.3 Basic Implementation Procedure

From the perspective of federation conceptual modeling, the construction of the mega infrastructure construction management federation model includes the following basic steps: problem definition, scenario conciseness, federate abstraction, federation relation abstraction, scenario model construction, and federation model integration and calibration. Furthermore, the construction of the mega infrastructure construction management federation model is often the repetition of this basic process in practical scenarios. Problem definition indicates that the content, boundary, and expected effect of the problem being studied should be clarified prior to the mega infrastructure construction management federation modeling, and it can be described using natural language. Generally, it is the complex management problems that should be described by the mega infrastructure construction management federation modeling rather than the simple ones. Scenario conciseness refers to the description and conciseness of the time, place, characters, reasons, and results of the problems occurring in the mega infrastructure construction management problems that are being researched. It also requires the identifying of the key scenario that affects the management problem, which means identifying the key scenario information that influences that management problem. Generally, because every mega infrastructure construction management activity has a corresponding management scenario, the scenario to every mega infrastructure construction management activity should be solidified. Federate abstraction refers to mega infrastructure construction federate modeling. First, the type and number of federates in the mega infrastructure construction management system must be determined, and the basic attributes, decision-making behaviors, and relationship network of these federates must be described. If the federates are management activities, they can be constructed in accordance with the cognitive framework of the general management activities. Federation relation abstraction occurs after the completion of federate modeling. This task involves abstracting the relation networks among the federates, such as task coordination relationships, interest clientage, right assignment relations, genetic kinship, and causal relations. Second, the federates and the holistic control system, the boundary between orchestration and autonomy rights, and the basic rules of communication should be described and abstracted to ensure normal interactions, combinations, and integrations among federates. Integration and calibration are concerned with the combination and assembly of the mega infrastructure construction management federation model and the verification of the validity, accuracy, and stability of the whole of model. This type of integration and calibration can be deduced by a mathematical formula and can be completed by computer programming and simulation.

From the perspective of model implementation and development, the mega infrastructure construction management federation modeling process can be divided into five steps: federation modeling requirements acquisition, federation modeling preparation, federation model design and development, federation simulation development and design, and continuous optimization. The concrete content and logic of these steps are presented in Fig. 9.19.

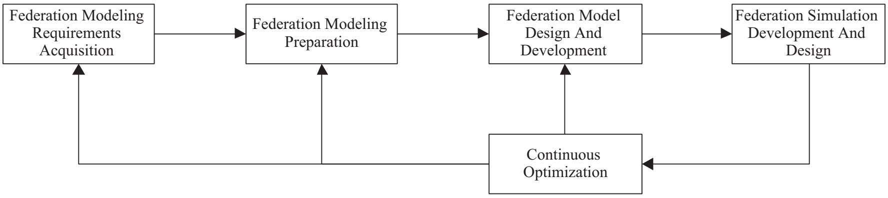

Fig. 9.19 Mega infrastructure construction management federation modeling implementation steps

Demand acquisition, which is the starting point of mega infrastructure construction management federation modeling, is guided by the demand for the ultimate user to consider the basic objectives, content, and conditions, task arrangements, and organization management of mega infrastructure construction management federation modeling. Starting from the perspectives of the users and the project, mega infrastructure construction federation management demand acquisition must transform the federation modeling problem space of its various management problems to user space and task space in the mega infrastructure construction management federation model. The methods and techniques of federation modeling that should be applied to specific management problems should be considered when refining the specific needs that are to be explicitly described.

The main tasks during the preparation phase of federation modeling include the planning and organizing of all types of resources that are needed for federation modeling, establishing a federation modeling organization team, drawing up a detailed modeling process plan, and developing collaborative rules and exception management methods. The resources of federation modeling include related theories, knowledge, technologies, talent, data, and information. The establishment of the federation modeling organization should follow the arrangement of the existing management organization of the mega infrastructure construction and should be based on the federation modeling coordination team that is composed of members from multiple departments. This team will assume full responsibility for the modeling of mega infrastructure construction federation. Detailed schedules should be made for the mega infrastructure construction management federation modeling, specific regulations for information communication among the different departments should be established, and rule-based methods to address exceptions should be developed.

The design and development of the federation model and simulation system are key steps of in the mega infrastructure construction federation. According to the mega infrastructure construction-federated simulation and the federation management general planning requirements, a federation modeling and simulation environment that supports a concurrent, heterogeneous, and distributive model and whose system is flexibly assembled, integrated, and separated, based on the existing model base, are necessary elements of the federated environment. The focal point of this environment lies in developing a public database that can support the exchange, mapping, and transformation interface among the different types of multi-instance concurrent and distributive model data and that can support all types of applications to enable model builders to conduct effective model federation and system simulation in a supportive environment. The design of the mega infrastructure construction management federation model and federation simulation references the federation simulation system development and design method promoted by the US Department of Defense in the 1990s (Dahmann et al. 1998; Sarjoughian and Zeigler 2000; Zhang et al. 2010) and draws on the theory and knowledge of building information modeling (BIM) and complex system modeling technology.

Mega infrastructure construction federation modeling is a process of gradual and continuous optimization. This iterative optimization is embodied not only in the great circulation of the mega infrastructure construction federation modeling general steps but also in the system requirements acquisition and preparation of federation modeling, in the design and development of the federation model, and in every sub-step of the federation simulation development and design, especially in that special attention should be given to continuously adjust and optimize the technology and simulation framework in the design and development of the federation model federation simulation.

9.3.3.4 Federation Based on BIM

In recent years, BIM (building information modeling), as a new engineering construction technology and concept, has become the focus of domestic and foreign scholars as well as people in the construction sector (Jian 2010; Becerik-Gerber et al. 2011; Azhar 2011; He et al. 2012). In some sense, BIM also acts as a model for complex physical engineering and management systems. Therefore, it is closely related to the federation modeling concept.

The idea of BIM originates from the 1970s (Yessios 2004), after which Charles Eastman (1999), Jerry Laiserin (2002), and McGraw-Hill Construction Information Company from Georgia Institute of Technology defined BIM in detail (Zhang and Wang 2012; Liu and Wang 2010). The US National Building Information Modeling Standard (NBIMS) defines BIM as "the digital expression of physical and functional properties of facilities; BIM is the shared knowledge resource, the process of sharing the information of this facility and providing reliable basis for all decision-making during the entire life cycle from the concept to the removal of the facility. In different phases of the project, different stakeholders support and reflect the respective responsibilities of the cooperative work through inserting, extracting, updating, and modifying the information in BIM" (He et al. 2012;Li et al. 2010).

As for the current application of BIM at home and abroad, BIM involves a 3-D dynamic visualization display of the construction scheme, a designing scheme test and construction simulation between different organizations or individuals, a deeper design for the purpose of efficiency, safety and environmental protection, 3-D models and the construction schedule of integrated buildings, and the realizing of the 4-D dynamic simulation and project push during the entire construction process of construction (Zhang et al. 2012). From the supporting and promoting purpose of BIM in developed countries, it can be concluded that to draft national BIM standards, IPD (integrated project delivery) requirements based on BIM should be promoted in government projects. Accordingly, all government projects must submit a BIM model of the entire life cycle of the project during the prophase decision-making stage. This means that all planning, design, construction, operation, and maintenance activities related to the project must be submitted. Furthermore, a unified, standardized, and orderly management of the follow-up project construction and project operation maintenance should be based on the BIM model (Xu et al. 2010; Guo et al. 2012).

The BIM model includes the basic data and core model for the design, planning, construction, development, and operation management of mega infrastructure construction management. That is, all of the relevant models can be integrated and federated through the BIM model, and the mega infrastructure construction management BIM technology is one of the core technologies of the federation modeling. Hence, the focus is on the management of the mega infrastructure construction life cycle, and as such, the major parties work together during the prophase decision-making stage of the mega infrastructure construction. Furthermore, the coordination and mutual understanding, testing, and improvement of all types of mega infrastructure construction design based on BIM are promoted throughout the project. During the prophase decision-making stage, all problems in construction and operation maintenance, including cost accounting, time schedules, risk management, green construction, and project knowledge innovation management, should be discovered through the virtual design, construction, maintenance, and management, thus ensuring mega infrastructure construction management quality and reducing management costs and risks.

9.3.3.5 Supporting Environment Framework

Based on high-level architecture (HLA) (Dahmann et al. 1997; Kuhl et al. 1999) and the federal information mode (FIM), the mega infrastructure construction management federation modeling support environment, respectively, constructs the BIM, assignment information model (AIM), and building information modeling (BIM). The BIM describes the physical properties, including geometry, space layout, internal structures, appearance, quality, durability, and stability, of the project entity and the natural environment of mega infrastructure construction management through the digitalization, parameterization, and modularization of the mega infrastructure construction BIM. Behavior properties, such as subject behavior, preference, and learning, can be described through the digitalization, parameterization, and modularization of the mega infrastructure construction BIM. Specific management objectives, contents, and processes can be described through the mega infrastructure construction management AIM, where functions such as definitions and modifications of mega infrastructure construction management tasks can be supported by a related management task database and process base, the details of which are presented in Figs. 9.20 and 9.21.

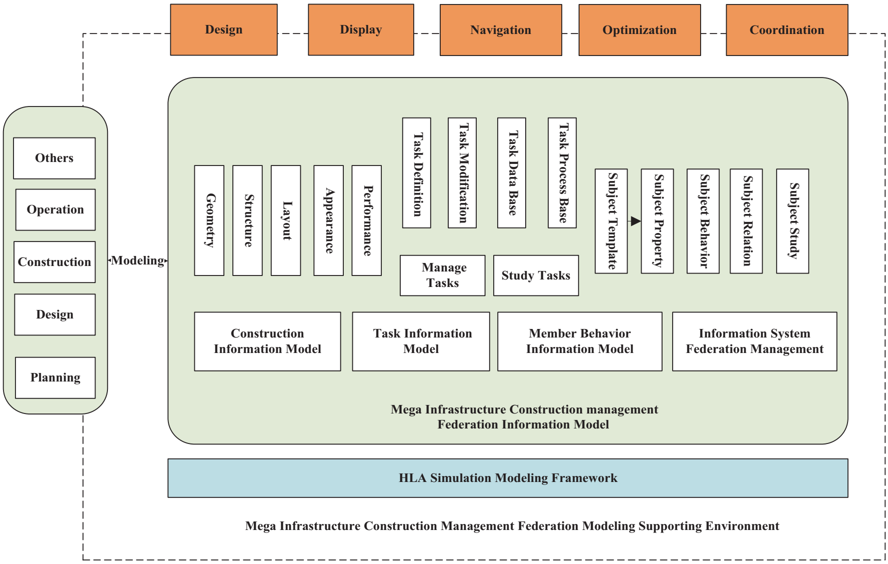

Fig. 9.20 Mega infrastructure construction management federation modeling supporting environment framework

From the perspective of the application function of mega infrastructure construction management federation modeling, this framework is the link between communication and cooperation, planning, design, construction, and operation subjects. The major application functions include supporting the dynamic design and virtual display of the construction entity geometry, layout, structure, appearance, and properties; providing order, safety, environmental protection, and intelligent navigation for construction planning, design, construction, and operation processes; optimizing the arrangement of engineering construction processes and resource allocation efficiency; and realizing the collaboration of the subjects, i.e., decision-making parties, participating parties, and operation party subjects, to complete the construction management tasks.

In the mega infrastructure construction management of the federation modeling support environment, the HLA, as the bottom simulation soft environment, possesses the characteristics of distributiveness, interactivity, heterogeneity, time and space consistency, and openness. As such, it can support the interconnection between distributed and heterogeneous simulation models and systems that are built by different participating organizations, enterprises, and individuals. Moreover, it supports the function of human-computer interaction. FIM, as the simulation database and model base, is an upgraded version of the traditional engineering building information model (BIM), and accordingly, it includes a multidimensional mega infrastructure construction management object model, management tasks and a management subject behavior model based on the construction management artificial society, and the construction management task

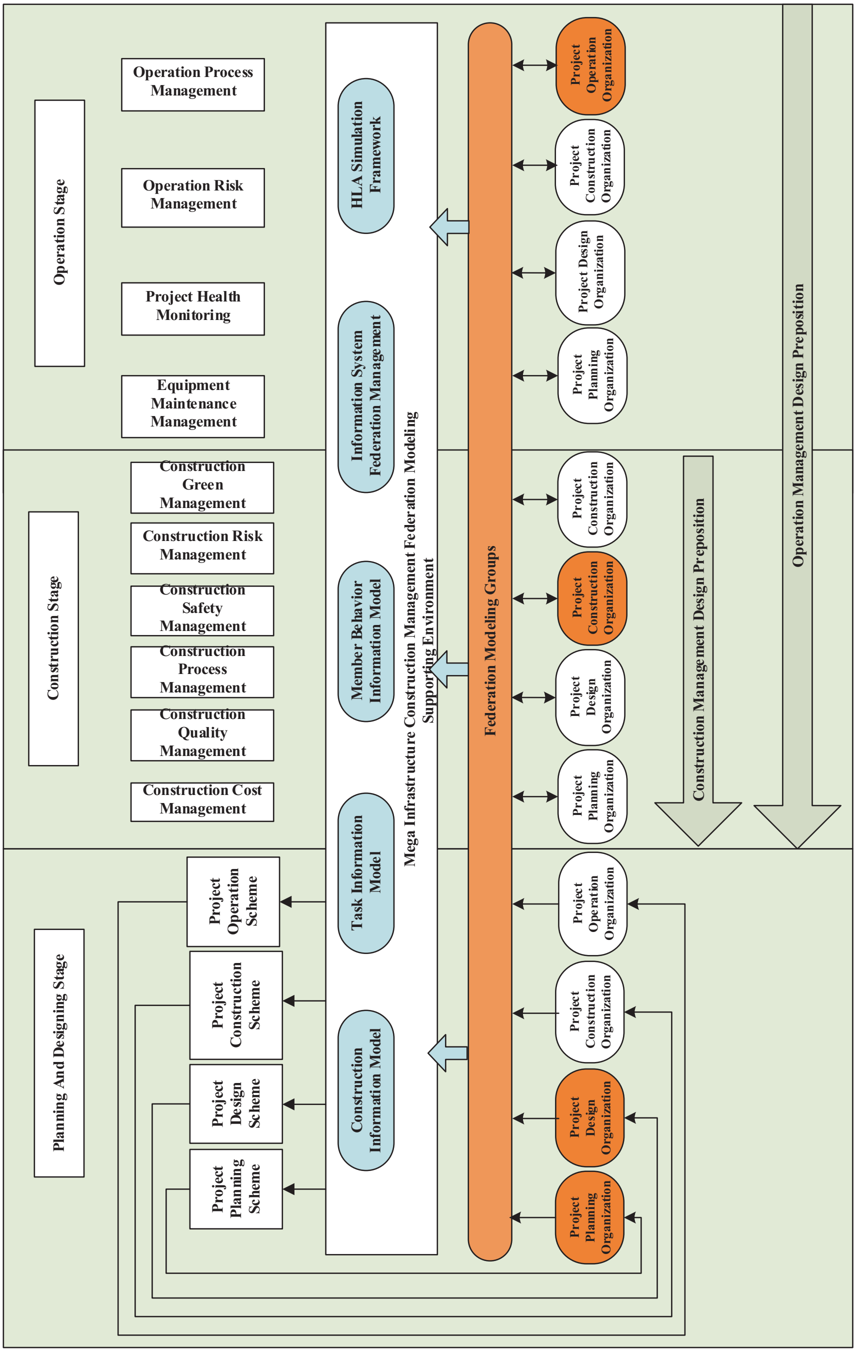

Fig. 9.21 Mega infrastructure construction management federation modeling task coordination framework

model. From the perspective of function, it has the advantages of being a flexible, convenient, consistent, scalable, adjustable, and reusable reconstruction. In addition, two communication interfaces should be established between the HLA and the mega infrastructure construction management information model to achieve the interconnection between the HLA and FIM.

Strengthening the connection between humans and machines is one of the important objectives of mega infrastructure construction federation modeling. One or more models from among the qualitative, quantitative, experimental, and physical models can be applied to describe any mega infrastructure construction management problem. With the proper modeling costs combined with complexity and feasibility, the development of federation models of different types, levels, and resolutions generally improves the depth of understanding regarding management problems of mega infrastructure construction. The mega infrastructure construction management federation modeling highlights enhancing the knowledge and decision-making levels with federation models of different types, levels, and resolutions while also emphasizing a reduction in federation costs and in the complexity of heterogeneous models, an improvement in the efficiency of heterogeneous models, and the acknowledgement of the five managements of mega infrastructure construction management, namely, whole processes, tasks, information, federates, scenarios, and lifespan, through the comprehensive utilization of the integration of the mega infrastructure construction management federation information model and a high-level simulation modeling framework.

9.3.3.6 Task Cooperation Framework

The task cooperation framework of mega infrastructure construction management federation modeling is the framework of the modeling process based on the cooperation of multiple members, in which the mega infrastructure construction management federation modeling support environment serves as the public platform for the task cooperation of all members. This functions as a platform for information communication and management, knowledge sharing and innovation, for federal modeling, and, more importantly, for supporting the smart management and navigation of the planning, design, construction, and operation schemes by planning, optimizing, and implementing schemes of mega infrastructure construction.

The mega infrastructure construction management task cooperation framework is also a framework of mega infrastructure construction integrated delivery, which requires that the subsequent planning, design, construction, and detailed design of all management activities be completed by the mega infrastructure construction management planning, design, construction, and operation departments before the establishment of the project or during the planning or design phase(Ma et al. 2014; Xu et al. 2010; Guo et al. 2012). This detailed design of the plan must be based on a relatively uniformed mega infrastructure construction management modeling support environment. The prepositioning of construction management design and operation management helps reduce the risk of management inconsistency and a lack of continuity resulting from the separation of time and space during every phase of mega infrastructure construction management. It also helps to predict problems that may exist in the mega infrastructure construction and operation management phases and thereby constrain and optimize the management behavior of the engineering construction and operation enterprises through traceable mechanisms to achieve functions such as consistency, traceability, and early prevention of problems in planning, design, construction, and operation management.

In the planning and design stage of mega infrastructure construction management, construction planning, design, construction, and operation management departments should complete all of the detailed activities of the entire project cycle with respect to design, analysis, and testing according to the requirements of the construction employer. Every member who participated is required to conform to the construction information model, task information model, and members' building information modeling based on the mega infrastructure construction management federation modeling support environment. For example, when submitting the construction quality management scheme, the construction management department should analyze all possible factors affecting the quality of construction materials, including the technical factors, human factors, and environmental factors, and incorporate those factors into the construction information model, task management information model, and members' building information modeling of quality management during the construction phase.

In addition, the construction of various types of information models and systems of mega infrastructure construction management involve relatively high technical requirements. The implementation of construction, integration, debugging, and operation of these information models should be commissioned by a professional federation modeling team. Meanwhile, the modification of the original planning and design scheme of any department, individual, or organization should be in accordance with the standard procedures, and all of the data and information related to mega infrastructure construction management should be managed by a unified information system and should provide the relevant functions, such as quick query, data storage, data analysis, and data display.

9.3.3.7 Visualization of Federation Modeling

Mega infrastructure construction management federation modeling is a complex management system. Specific ideas and methods, such as a federation based on BIM, a supporting environment, and a task cooperation framework, to control this complex system have been discussed in various sections of this book. Based on the same objective, the ideas and methods of visualization in mega infrastructure construction management federation modeling are now detailed.

The nature of mega infrastructure construction management visualization is a type of visual modeling technology, whose purpose is to degrade the complexity of mega infrastructure construction management and its federation modeling management. The implementation technique involves the digitalization of a high-quality and transparent platform of mega infrastructure construction management and its federation modeling. This platform must include modern information science and technology, such as computer simulation technology, data visualization technology, virtual reality technology, computer-aided design, cloud computing, and enormous amounts of data.

The realization of the visualization of mega infrastructure construction management federation modeling involves three steps or objectives.

The first step is to realize that the digitalization of the mega infrastructure construction management elements includes the digitalization of the management subjects, e.g., human resources, financial resources, material resources, information, time, and space; management methods, e.g., incentives, penalties, communications, coercion, persuasions, and exchanges; and management processes, e.g., setting and decomposition of goals, management rule determination, management resource allocation, organization and implementation, process control, and effect evaluation. The federation, based on the BIM in Sect. 9.3.3.4, is a basic way to realize the digitalization of mega infrastructure construction management elements, especially the construction of the management task information model and management building information modeling, which are the specific methods of the digitalization of the mega infrastructure construction management elements and stand as a good reference.

The second step involves realizing the transparency of the mega infrastructure construction management federation modeling elements, which requires adhering to the transparent rules and processes of mega infrastructure construction management federation modeling. The transparency of mega infrastructure construction federation modeling is based on the transparency of the modeling rules and processes of the mega infrastructure construction management federation modeling objectives, methods, processes, language, technology, and implementation subjects, along with the corresponding management permissions. For example, to digitalize and create a graphic of the mega infrastructure construction federation modeling task cooperation framework, as discussed in Sect. 9.3.3.6, will, to some extent, achieve the transparency required of mega infrastructure construction management federation modeling.

The third objective or step is to achieve a platform-based mega infrastructure construction management that can better integrate and that can demonstrate effectively the mega infrastructure construction management federation modeling process and effects through an information technology platform that fully shares information and resources. To accomplish this, it is necessary to apply software engineering technology, heterogeneous model integration technology, and middleware technology. For example, integrating the task cooperation frameworks based on BIM federation and a supporting environment, as discussed in Sects. 9.3.3.4, 9.3.3.5, and 9.3.3.6, will facilitate the implementation of a platform-based mega infrastructure construction management.

Finally, the existing computer-aided design technology, digital visualization, and virtual reality technology are applied to demonstrate for the top decision-makers, floor managers, and model builders the mega infrastructure construction management-federated modeling process, modeling quality, and effect in a way that more easily reflects the characteristics and nature of the management problem, that is more easily understood and communicated, and that more easily achieves flexible construction and task cooperation.

9.3.4 The Development and Operation of Federation Model for Mega Infrastructure Construction Management

The focal point of the development and operation of mega infrastructure construction management federation modeling covers two aspects, namely, the development of the mega infrastructure construction management federation model, which possibly can be perceived as a model system composed of a series of federates, i.e., management issues, and the realization of the supporting environment for the development of the mega infrastructure construction management federation model. Hence, it is necessary to describe the development and operation of the mega infrastructure construction management federation modeling from the perspective of the realization of software engineering and from the perspective of the development and operation of the federation modeling supporting platform. To realize such tasks, especially the realization of a supporting environment to the development of the mega infrastructure construction management federation model, one can reference the federal development and operation process model initiated by the US DMSO in the 1990s (Dahmann et al. 1997, 1998; Wilcox et al. 2000; Dai and Hou 2005; Dai and Jiang 2002). Based on this reference, steps for the development and operation of mega infrastructure construction management federation model can be identified.

9.3.4.1 The Definition of Objectives

To define the objectives of the mega infrastructure construction management model development goal requires specifying the objective and the process of the objective declaration based on the requirements of, for example, the federation model, system, management, and modeling process. The specific content and logical relationship is presented in Fig. 9.22.

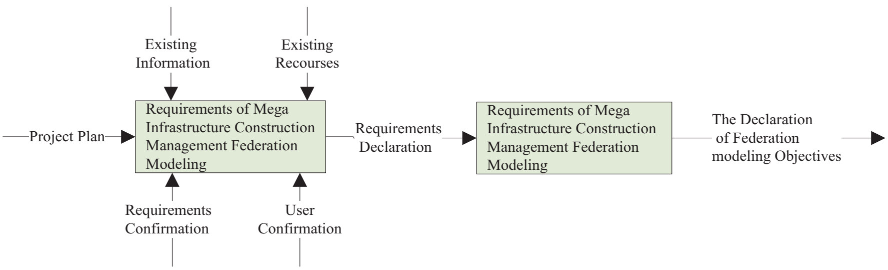

Fig. 9.22 Mega infrastructure construction management federation modeling objectives and the declaration of objectives

Description tools, such as the data flow diagram (DFD), the unified modeling language (UML), and the function modeling of comprehensive definition language (IDEFO), can be applied to the definition of mega infrastructure construction federation modeling objectives, which include describing the expected results (model or the simulation system) the users are capable of achieving. These achievements include the expectation to realize the dynamic display and roaming function of mega infrastructure construction federation modeling, the simulated navigation during the construction phase, the friendly interoperability and data calculation ability, or building a model that represents the integrated modeling of macro decision-making issues and is capable of conducting an in-depth study of issues regarding construction environment protection.

It is important to note that the demand for a federation model of mega infrastructure construction management is generally described using natural language. Because natural language is usually general, ambiguous, and imprecise, it results in the need to use tools to create a data flow diagram (DFD)), a unified modeling language (UML), and a functional model of comprehensive definition language (IDEFO) to transform it to specific, detailed, and clear requirements. The members from the technical team of the mega infrastructure construction management federation model can develop a process that will accomplish the necessary transformation.

The requirements for the mega infrastructure construction management federation modeling begin from practical needs, such as the actual management issues and the final application and simulation of the model and adherence to the user-needs-oriented principle, which means insisting that the refining of the related requirements be performed by the participants of mega infrastructure construction management, including pre-decision-makers, interim participants, and anaphase operators, and especially the organizations operating during the interim and anaphase of mega infrastructure construction.

9.3.4.2 The Development of a Conceptual Model

Based on the federation model for mega infrastructure construction management and its realization, the development of a mega infrastructure construction management federation conceptual model (FCM) describes the space of issues regarding the related model, system, and management federation of mega infrastructure construction management, including the development of the scenario of mega infrastructure construction management, system, and management federation; the development of the conceptual model of the mega infrastructure construction management model, system, and management federation; and the development of the requirements of the mega infrastructure construction management model, system, and management federation. Fig. 9.23 provides the detailed content and logical relations.

The development of the federation modeling scenario for mega infrastructure construction management includes descriptions of the type, quantity, attributes,

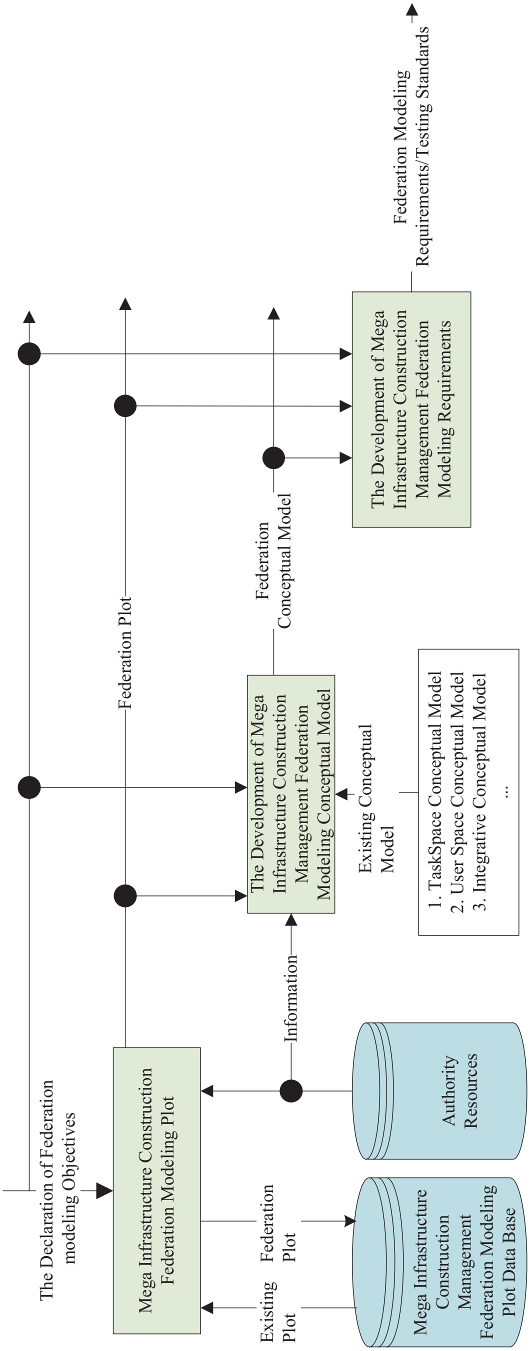

Fig. 9.23 Mega infrastructure construction management federation modeling conceptual model development

behaviors, interactions, relations of the federation entity involved in the mega infrastructure construction management issues, and the federation entity's overall function evolution whose environment changes over time. Additionally, the development of the scenario involves the standard description of the interactive function among the federation entities and between the entity and the environment. It should also describe the initial, operating, abnormal, and termination conditions of the model, system, and management federation scenarios.

An analysis of the mega infrastructure construction management federation conceptual model (FCM) involves the transformation from the federation scenario of the model, system, and federation of the management of mega infrastructure construction management, from the existing conceptual model that includes the conceptual model of the task space, user space, and integrated conceptual federation model, and from authoritative data to the conceptual model of mega infrastructure construction management federation modeling independent from specific implementation to provide support for building a more detailed federation model. Various methods of system analysis can be adopted and incorporated into the analysis of the mega infrastructure construction management federation model, such as the object-oriented method and the process-oriented method. Because the construction of federate models, including artificial social information, should be included in mega infrastructure construction management federation modeling, an object-oriented analysis method will be one of the primary methods for the analysis of the mega infrastructure construction management federation conceptual model.

The development of the mega infrastructure construction management federation modeling requirements further refines the targets, scenarios, and concepts of federation modeling, for example, what objects and behaviors are included in the federation modeling conceptual model, what types of federates can be applied to express these objects and behaviors, and what are the relevant testing standards.

9.3.4.3 Federation Design

The primary task of the federation design of mega infrastructure construction management federation modeling is the selection and evaluation of mega infrastructure construction management federates, the allocation of corresponding functions for each federate, and the formulation of the detailed plan of the development and implementation of the federates. Concrete content and logical relations are presented in Fig. 9.24.

The selection of mega infrastructure construction management federates involves using federation modeling scenarios as the blueprint. Furthermore, the key members involved are extracted to describe the attributes, behaviors, and environment information of all members. The criteria for selection are fundamentality, independence, reusability, and interoperability, indicating that it is a basic simulation unit. Therefore, those with the autonomous capability of simulation units, those with high reuse rates, and those other simulation units with relatively high rates should be selected. For example, in mega infrastructure construction management, selecting

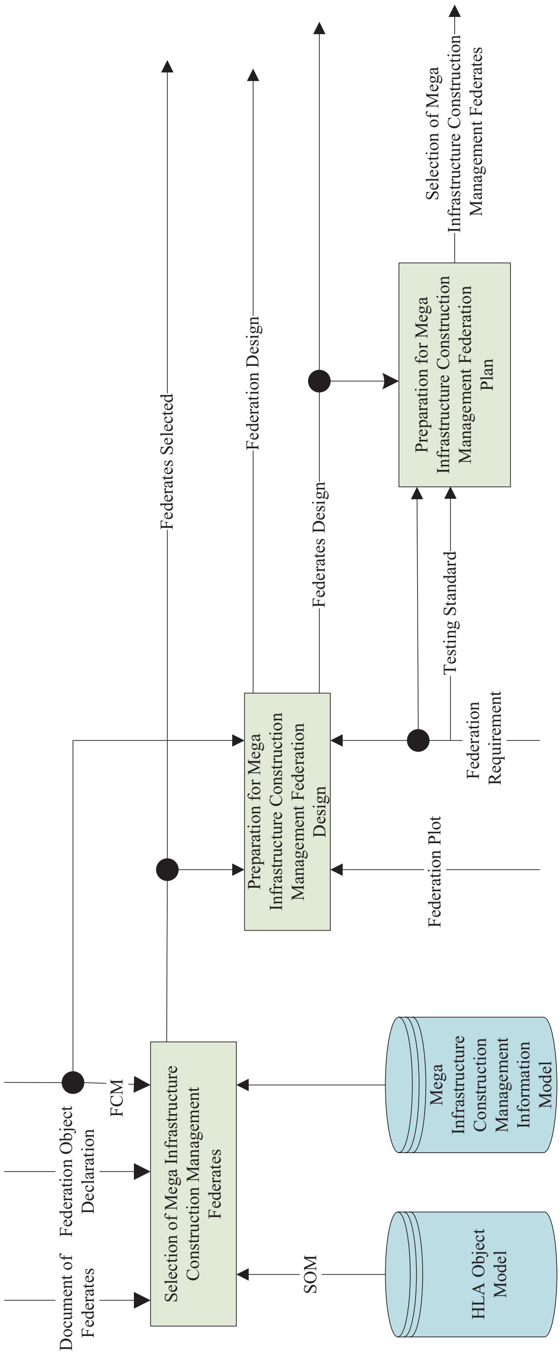

Fig. 9.24 Design of mega infrastructure construction management federation modeling

a construction information model that embraces high interoperability and reusability as a federate can serve to support other simulations with basic data, and it can become an extremely basic construction management information model.

With the input of the selection of federates, the federation scenario, and the requirements, the preparation for the mega infrastructure construction management federation design defines the functions and behaviors of the federates and the federal relationship among the federates. Furthermore, attention should be given to whether the degree of specificity of the definition of those functions and behaviors is sufficient, whether its flexibility is capable of adjusting to a wide variety of updated requirements, and whether the theoretical support is sufficiently authoritative.

The preparation of mega infrastructure construction management federation modeling federation plan aims to develop a collaborative plan that provides guidance for the development, testing, operation, and verification. This requires the close communication of information and collaboration on tasks among the federates.

9.3.4.4 Federation Development

The task of the federation development of mega infrastructure construction management federation modeling includes three factors, namely, the development of the federation object model (FOM), the establishment of the federation agreement, and the implementation of the federates' amendments.

The development of a mega infrastructure construction management federation modeling of the federation object model (FOM) refers to the formulation of the rules of data, information and energy exchange among the federates, and the guarantee of this interaction at the time of the operation of the mega infrastructure construction management federation system to achieve the federation objectives. The development of the mega infrastructure construction management federation modeling of the federation object model (FOM) differs from the discovery of new federates in that it integrates the basic, independent, reusable, and interoperable simulation units, systems, or models based on the existing simulation system or model. That is, there is no need to redevelop the already existing simulation unit, system, or model. Instead, it is the communication interface among federates that should be established. In the construction of the interface, some of the simulation units, systems, and models may be modified; however, this is only a partial modification.

Although the FOM has recorded the rules that must be adhered to during the interaction of the federates' data, information, and energy, it is unable to describe many of the interaction rules under which the circumstance of the federation agreement should be established to achieve the integrity, consistency, and interoperability of the interaction of the federation rules. The federation agreement of the mega infrastructure construction management federation generally involves the following factors: (1) a federation scenario data agreement, (2) a federation time agreement,

(3) a federation synchronization control agreement, (4) a federation algorithm agreement, (5) a federation system operation control management agreement, and (6) a federation data distribution management agreement.

The implementation of the amendment of federates refers to the specific implementation of transferring the federation agreement to a federate, which resembles the system implementation process of general information systems. Before the implementation of the federates amendment, the internal modification of federates may be covered, and those outside of the HLA framework should be integrated into it, which requires that consideration be given to the compatibility, cost, and reusability of the amendment.

9.3.4.5 Federation Integration and Test

The federation integration and test of mega infrastructure construction management federation modeling refers to the implementation of system integration and tests of federates, which includes three aspects, namely, the development of the federation operation plan, federation integration, and the federation test.

The formulation of a federation operation plan for mega infrastructure construction management federation modeling involves federate protocol integration, the test and operation management process, and related requirements. The necessary records of related integration processes should also be included. Mega infrastructure construction management federation modeling mainly encompasses the interconnection plan of the federates, the correctness of the federates, plans for verifying the effectiveness and performance evaluation of and manual preparation for the plan, and various information required to improve, to as great a degree as possible, the operations of the federation.

The federation integration of mega infrastructure construction management federation modeling addresses the implementation of the interconnection of software and hardware in accordance with the federal member interconnection plan to ensure a holistic, interoperable federation environment formed by every federate. Federation integration is a step-by-step process during which the focus should be on the importance of step-by-step testing and checking and on the issue of global integration testing and checking.

The federation test of mega infrastructure construction management federation modeling assesses whether federates are capable of realizing the requirements of the mega infrastructure construction management federation modeling objectives, and it especially tests whether the interoperability degree among federates meets the federation modeling and simulation requirements. According to test objects, the mega infrastructure construction management federation test can be divided into a federates test and a federation test, whereby the former focuses on testing the federates' coding accuracy and integration compatibility and the latter focuses on testing whether the federates and the federation meet the specific federation modeling required objectives. The test content includes the application test of federates, an integrated test of the federation, a functional test of the federates and the federation as well as a plot test, exception test, and performance test. Unit test, performance test, and exception test methods, which are generally integrated in the software engineering, can be applied to the federate and federation tests.

9.3.4.6 Federation Operation and Result Processing

Federation operations and result processing of mega infrastructure construction management are the final steps in the development and operations of the federation model. The objective is to ensure the operations the federation and process the output of those operations. The holistic scheme of control and monitoring management should be developed in advance to ensure that the federation participants can take part in the process of mega infrastructure construction management federation modeling and simulations. Result processing includes the storage method, statistical analysis, and design and management of the visual display of output data. Federation modeling and simulation can also be applied when outputting data to form a normative analysis of the results of the report.

The advanced research method regarding the issue of mega infrastructure construction management, i.e., mega infrastructure construction federation modeling, is well discussed, and its several salient features are well defined:

1. It is a method system for the complex integrity research of mega infrastructure construction management, not just a method for the research of specific issues.
2. It is a multifunctional platform whose core function is to provide a variety of environment and support conditions for the study of various management issues.
3. It is a cross-discipline and multi-discipline technical route discipline that fully embodies comprehensive integration, and its core and key technology lie in the feasibility of covering and commanding the complex integrity of mega infrastructure construction management.

It is not possible to build such a platform with such a small number of people and within a relatively short period of time because, while it displays a powerful function of its own, the complexity of the system and the arduousness of the realization process are set. Though this complexity can be understood as mega infrastructure construction management of federation modeling, it is a mega infrastructure construction issue. However, once a concrete federation model has been constructed, it provides the powerful decisions, analyses, and management support competence needed throughout the life cycle of the project, and it exhibits a relatively strong adaptability toward other mega infrastructure constructions. Accordingly, it will result in an enormous all-around impact on the effectiveness of mega infrastructure construction management research.

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Chapter 10
Intelligent Management of Mega Infrastructure Construction

The exploration and reflection of the management theory of mega infrastructure construction is founded on the construction practice within a certain period and certain scope and on the current technological environment confronted by construction projects. However, the advancements in society's technological environment, much like those in practice, are endless.

Thus, as theoretical reflection and exploration are also endless, it is important to identify the developmental tendency of mega infrastructure construction practice and social technology and determine how they boost and influence the overall revolution of mega infrastructure construction management. Rather than future theoretical issues, these are current issues that have already presented themselves in the field.

To gain a better understanding of mega infrastructure construction management, it is first necessary to understand the increasing complexity of mega infrastructure construction practice.

10.1 The Increasing Complexity of Mega Infrastructure Construction

Though the cognitive principles of the complex system and the complex entirety of mega infrastructure construction and mega infrastructure construction management have been established, the types of complexity changes that appear within the scope of complexity in future mega infrastructure construction and mega infrastructure must be identified.

The overall complexity of prospective mega infrastructure construction as described from two dimensions, construction technology complexity and construction management complexity (Bosch-Rekveldt et al. 2011; Puddicombe 2011), are presented in Fig. 10.1.

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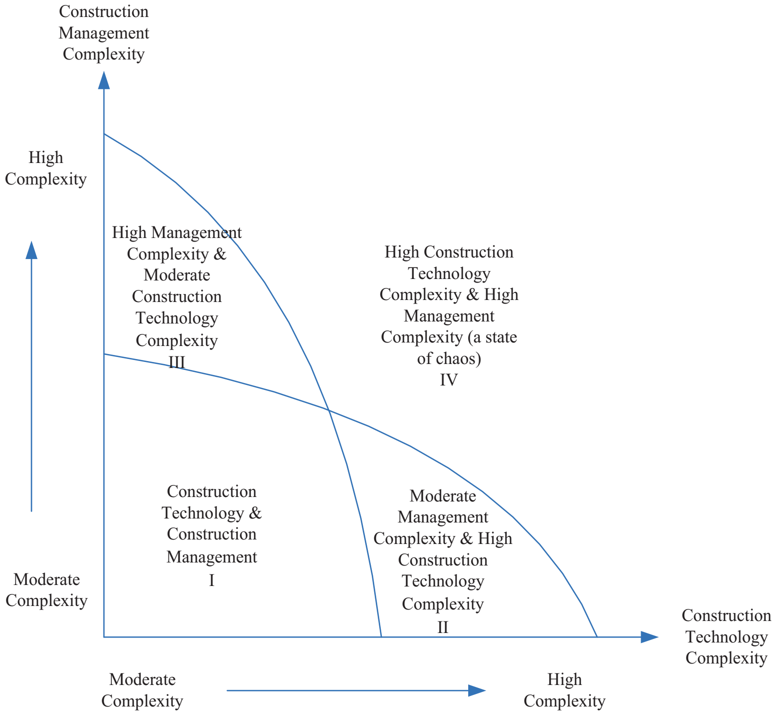

Fig. 10.1 The overall complexity of mega infrastructure construction

As presented in Fig. 10.1, mega infrastructure construction in Region I manifests as moderate complexities in construction technology and construction management, whereas in Region II, it manifests as moderate management complexity but high construction technology complexity. High construction technology complexity means that, for example, the materials, equipment, and processes of the hard system for mega infrastructure construction are not yet complete, and the necessary principles and laws of construction technology are not entirely clear. In Region III, mega infrastructure construction manifests as moderate construction technology complexity but high management complexity. High management complexity means that, for example, there are difficulties in perceiving, coordinating, and implementing the complexity of mega infrastructure construction management and that it is also difficult to effectively and orderly control the complex entirety of management. Finally, in Region IV, mega infrastructure construction manifests simultaneously as high construction technology complexity and high management complexity, which indicates that, as a whole, the degree of complexity is in a state of chaos.

It is further noted that the high overall complexity of mega infrastructure construction is merely a cognition of the whole, i.e., a vague conception. It is vague because, in the future, there will be new cognitions and conceptions of the complex system and the complexity of the system, and moreover, owing to the tremendous progress in human wisdom and capabilities, what is currently deemed complex will become less complex in the future. However, once complex concepts are understood and perceived as no longer complex, what is regarded as high complexity today may be regarded as moderate complexity in the future.

Actually, mega infrastructure construction with high overall complexity has existed for years. In a certain sense, China's Three Gorges Project, built approximately 30 years ago, can be considered a project with high overall complexity. Moreover, the incessant 30-year debate regarding the effect of the mega infrastructure construction decision-making has spoken volumes with respect to the comprehensive evaluation of the highly complex decision management and decision-making scheme (Lu et al. 2008).

Another typical, albeit more current, case is the Cross-Bohai Straits Passage Project, which eastern China intends to build to connect Shandong Province and Liaoning Province, which can also be considered a highly complex mega infrastructure construction project with respect to management and construction technology. This planned passage project is a complete submarine tunnel with an overall length of 123 km that will convey automobiles by train at a speed of 220 km/h.

The Cross-Bohai Straits Passage Project, with a lifespan of 100 years, will create a new multiplexed system that involves the project itself as well as the society and natural environment of the surrounding areas after completion. In this way, the project will inevitably have an extensive, lasting, and profound impact on the geological, ecological, social, and economic environments in the project area during the construction process and the prolonged period of operation henceforth. Furthermore, the project will likely increase the risk of serious natural ecological disasters, though such disasters have never occurred in the area. Incurred by interrelated subsystems of geology, ocean currents, living creatures, atmosphere, and artificial projects, this type of evolutionary risk is difficult to identify and forecast using the traditional project demonstration method. Hence, the preliminary planning and demonstration of the Cross-Bohai Straits Passage Project must fully identify any major potential risks to which the project may contribute within its long lifespan, including a variety of large-scale evolutionary risks of serious natural disasters that may emerge in large numbers. This presents a new and serious challenge to the high complexity of the demonstration of the Cross-Bohai Straits Passage Project, and it is therefore considered dangerous to underestimate this type of risk by employing the traditional project demonstration method.

For instance, with respect to the geological environment, geological conditions in the area of the Cross-Bohai Straits Passage Project are quite complicated. For example, the seafloor is characterized by a rugged terrain that is traversed by grooves and ridges and descends from west to east, and on both sides of the Bohai Straits, there are numerous fracture zones. On August 22, 2014, regarding the Cross-Bohai Straits Passage Project, the China Earthquake Networks Center stated, the "Tanlu seismic belt stretches from the Heilongjiang River in the north to the Yangtze River in the south, runs through the eastern mainland of China from north to east, and extends more than 2400 km. As one of the main fault zones in the giant fault system in northeastern Asia, it has undergone many massive earthquakes in history" and is still active. Some geologists even draw the analogy that the geological situation of the seafloor of the Bohai Bay is similar to a broken porcelain plate still in its original shape, and thus, it is too fragile to survive repeated damage and must therefore be treated with great care. However, as high-speed trains continue to travel through the cross-straits tunnel for an extended period, will it cause this fragile porcelain plate—the seafloor of the Bohai Sea—to be further fractured, a situation that could lead to severe geological disasters such as earthquakes? There must be clear answers to this type of large-scale evolutionary risk of deep uncertainty incurred by the Cross-Straits Passage Project. Thus, under the guidance of the new demonstration theory built upon the high complexity of mega infrastructure construction, it is necessary to draw a conclusion that can stand the test of tie and that is based on adequate evidence and data derived from a series of scientific explorations and experiments.

With respect to the lifespan of the project, the Cross-Bohai Straits Passage Project is a super project designed to last 100 years. Hence, will the construction process and its future operations stimulate new physical factors and conditions that may continue to accumulate and be reinforced over time and, as a result, cause settling, cracking, and collapsing to the project due to geological, biological, and ocean current erosion, or will it give rise to earthquakes? These questions, too, must undergo the quality evolutionary analysis of complex projects. Only through demonstration analysis aided by technologies, such as system simulations of multi-level, multidimensional, multi-scale, and multi-granularity projects scenario, will it be possible to predict phenomena and establish, step-by-step, laws to manage potential disasters and subsequent phenomena (Mishra et al. 2013; Tolone et al. 2004).

In addition, with respect to the ecological environment, the construction of the Cross-Bohai Straits Passage Project and its long-term operation of 100 years may exhibit significant influence on the evolution of the marine ecosystem of the Bohai Sea and cause enormous damage to the marine ecosystem and the living environment of marine wildlife in the Bohai Bay. These impacts will be the result of a transfer-diffusion-evolution process of systematic natural disasters on a large spatiotemporal scale. Once a disaster occurs, it will exert relatively disastrous effects on the Bohai Bay, a natural system characterized by enclosed waters, a poor hydrodynamic long water cycle, and a fragile ecosystem. As a consequence, a modern, multidisciplinary approach should be used for demonstration and research whereby potential ecological disasters are first analyzed, and a reliable contingency plan to preclude and reduce potential disasters is then formulated.

There are additional similar evolutionary risks with which there is a lack of experience as well as an inability to control them. If these risks are seriously underestimated when identifying and verifying them, corresponding consequences can be catastrophic for the country, the society, and the natural ecosystem.

Accordingly, it is necessary to fully understand that the Cross-Bohai Straits Passage Project is a project of deep uncertainty, high risk, and highly integrated complexity with respect to both management and construction technology. Furthermore, regarding the demonstration of the project in China, or even the world as a whole, many highly integrated complex problems will be encountered for the first time.

To ensure that the demonstration of the Cross-Bohai Straits Passage Project is of good quality and of a scientific nature, it is important to ensure that the priority of the demonstration is to identify and predict large-scale risks and disasters that the project may encounter throughout its long lifespan and discover corresponding measures for preventing and reducing such disasters as well. Accordingly, it is necessary to formulate demonstration objectives and a demonstration system that incorporates the high complexity of this mega infrastructure construction. To formulate the demonstration system, the interrelationships among the multiple subsystems, such as society, the economy, ecology, and humanities, must be considered. However, to conduct an integrated analysis of objectives, interactions among objectives, conditions, and norms of decision-making must be embodied, and connections among them must be established (Holland 1995; Sheng and Jin 2012). Although certain new and unique demonstration objectives and demonstration issues may emerge for the first time ever, these issues and objectives must be thoroughly understood and clarified, and they should neither be simplified nor disregarded.

In addition, the Bering Straits Bridge, which is to be constructed by an international engineering field, is a transport mega construction connecting Asia and North America. Once completed, it will become another miracle in man's architectural history. According to the program planning, the bridge will be nearly 40 km long and consist of over 220 piers, each weighing millions of pounds, whose purpose is to resist the enormous pressure from the deep-water ice in the Arctic Ocean that weighs millions of tons. The bridge is in an extremely harsh environment, specifically, a frigid climate that is subject to frequent snowstorms and shrouded in fog. In the winter, the temperature can reach below −45 °C, and the surface of the straits freezes over with a layer of ice that is more than 2 m thick. With the aim to build the bridge in such a severe environment and to overcome obstacles that include colossal icebergs, turbulent seawater, and low temperatures of −40 °C, the engineering materials, construction machinery equipment, and, especially, the perception of the relevant construction principles, technical laws, and management must all demonstrate highly integrated complexity and first-ever risks in the world due to the shortage of cognition, information, and knowledge (Stetson and Mumme 2016).

A series of super creation projects envisaged and planned by mankind include mega infrastructure constructions integrated with high complexity, e.g., the submarine tunnel project of the Bering Straits, which is up to 105 km in length; the automatic underground freight and railway project traversing the Alps from Rosenheim to Verona, whose total length of single tunnels exceeds 500 km; the tunnel from Lyon in France to Torin in Italy, which is approximately 54 km long; and China's Cross-Qiongzhou Straits Passage and Cross-Taiwan Straits Passage.

The management idea regarding this type of highly complex mega infrastructure construction may extend beyond that which has been advanced in this book in that the complexity of issues must be classified and graded rather than degraded and then coalesced effectively with the on-site executive capacity for project management. For example, among the classes of complex issues, there is the class of basic or moderately complex issues, namely, I-level complex issues. Then, according to their degree of complexity, issues are graded as II-level, III-level, etc., from low to high. Highly complex mega infrastructure construction can be managed in a multi-scale manner based on the complexity levels of the issues whereby the management idea is to degrade complexity, step by step, from a high level to a low level until it coalesces effectively with the on-site executive capacity for project management.

In other words, during the management process of highly complex and integrated mega infrastructure construction, even in the future, complexity degradation will be a vital fundamental principle. However, since there are currently multiple levels of complexity, it is suggested to change the complexity degradation mode from the present just-for-once mode to a more-than-once, step-by-step mode.

10.2 The Era of Intelligent Internet

There have been several modern information technological developments in recent years that are perceived by society as "big events" that have had substantial influence on the building and management of current mega infrastructure construction.

First, the invention of the Internet has given rise to great global changes and revolutions. The Internet is a global computer network comprised of different types and scales of independent computer networks. In this sense, the Internet is an enormous global information and service resource that connects computers with humans.

With smartphones, tablet computers, and mobile Internet populating the market, the era of mobile interconnection, which is best represented by the mobile Internet, has emerged. This mobile interconnection, which combines the Internet with mobile communication, provides an open basic telecommunication network conclusive of voice, data, and multimedia. Based on the definition of terminal, users can obtain mobile communication network service and Internet service via the mobile Internet using mobile phones, netbooks, laptop computers, tablet computers, smart books, and other mobile terminals.

Cloud computing was invented in 2007. It is an addictive use and delivery model that is founded on relevant, contemporary Internet service and provides dynamic, scalable, and often virtualized resources over the Internet. As such, cloud computing works by distributing computations throughout an enormous number of allocated computers rather than through local computers or remote servers, thus simulating the operation of the company's data center to reflect that of the Internet. In this way, the company can switch resources according to the needed applications and then access computers or storage systems based on the requirements.

Thus, over a brief period of time, the concept of the Internet of Things was proposed based on the Internet concept. The Internet of Things means to connect all things with the Internet via information sensors and to conduct information exchange, namely, things connected, with the aim to realize intelligent recognition and management. Thus, the Internet of Things is the Internet connection of things, and as such, it has two meanings. On the one hand, the core and basis of the Internet of Things is the Internet, as denoted by an extended and expanded network based on the Internet. On the other hand, the client extends and expands beyond this to any item, i.e., it involves the conducting of information exchange and communication throughout the Internet.

Built upon cloud computing and Internet environments, the Internet of Things adopts suitable information security mechanisms that offer safe, controllable, and personalized real-time online monitoring and location re-seeking. In addition, the Internet of Things offers an alarm linkage system, a dispatch and command center, planning management, remote control, safety precautions, remote maintenance, statistic report forms, decision support, and lead desktop and other management and service functions. In this way, the Internet of Things can realize an effective, energy-saving, safe, and environmentally friendly integration of management, control, and operation of all items.

In 2008, the concept of Big Data was proposed. Big Data, also known as massive information, refers to the data that cannot be obtained, managed, and collected as useful information to help companies operate and identify more positive goals in a reasonable time using man's brains and mainstream software tools. Generally, Big Data are an enormous number of dynamic and continuous pieces of information that can be obtained through new systems, new tools, and new models and then used to achieve insightful information with new values. Accordingly, Big Data can be used in all walks of life to sort and analyze the enormous amount of data collected by people to realize the effective use of information.

With respect to technology, the relationship between Big Data and cloud computing is as close as the two sides of a coin. Certainly, Big Data cannot be managed by a single computer. Rather, it must be processed by distributed computers, as the features of Big Data are in the mining of the enormous amount of data, which must rely on distributed processing, a distributed database, cloud storage, and virtualization technology supported by cloud computing.

In this way, the Internet, the Internet of Things, cloud computing, mobile intelligent terminals, and other significant achievements in modern information technology are combined to construct an intelligent platform for infrastructure projects, and hence, humans enter an era of the intelligent Internet founded on this platform.

Specifically, *the intelligent Internet is an intelligent network that is grounded on the Internet of Things technologies and is transmitted by a platform type of intelligent hardware. Combining cloud computing and Big Data applications, the intelligent Internet collects, manages, analyzes, and applies information throughout intelligent terminals, the cloud service, and even humans. It has comprehensive high-speed capacities to move, analyze, and mine Big Data, IntelliSense, and applications; it has the service capabilities necessary to penetrate and integrate into traditional industries and improve them; and it can connect every walk of life and conduct online and offline trans-boundary management* (Netease. The Era of the Intelligent Internet Has Come Quietly! [report on the Internet]. [rev 2016 July 26; cited 2016 August 5]).

As suggested, as the complexity of the system of future mega infrastructure construction increases, so, too, the level of difficulty related to construction and technology increases, and an increasing number of new technologies, new materials, new equipment, and new crafts will emerge from among construction projects. This tendency results in overall revolutions not only to the construction enterprises and construction industries but to the overall engineering environment of mega infrastructure construction. Furthermore, the development of mega construction's social and technological environments not only offers unprecedented powerful technology support to the building and management of mega infrastructure construction, but it also guides and promotes tremendous changes in construction practices and management models while mutually integrating with mega infrastructure construction. For instance, intelligent Internet technologies have played an increasingly vital role in the revolution of building practices related to mega construction, and they will facilitate innovations in management modes and management theories of mega infrastructure construction.

To gain a better understanding of these changes, the possible mega infrastructure construction projects and management revolutions that may occur after the integration of the increasing mega infrastructure construction complexity and modern information technology represented by the mobile interconnection are forecasted and analyzed.

10.3 Intelligent Construction of a Mega Infrastructure Construction Project

First, the construction mode of mega infrastructure construction, which is characterized as people oriented, standardized, refined, industrialized, and information based, is under universal promotion among current mega infrastructure construction projects. For example, the visual model (BIM) of the physical world and the function of construction play an important role (Gu and London 2010; Cao et al. 2015); engineering materials in large quantities and industrial production of construction components, along with automation technology, are being widely applied; technologies for the real-time monitoring of the main equipment and the hard system of construction and for the diagnosing of health continue to be improved; and Big Data technology, with the Internet of Things Internet and cloud computing as its infrastructure, is playing an increasingly major role in the approval, design, demonstration, and decision-making of mega infrastructure construction (Whyte et al. 2016; Halttula et al. 2015).

Together, these advancements are bringing about profound changes in the construction practices of mega infrastructure construction projects. For example, the technical thinking, which coalesces with the simulated world of construction information through the hard system of physical construction at its core, continues to realize and optimize the function of construction management and enhance the comprehensive quality and management efficiency of construction. *This technical thinking that applies Internet technologies to mega infrastructure construction is called the construction of the mega infrastructure construction project plus Internet*.

By applying this concept to a mega infrastructure construction project, the impact of linking has been enhanced, and people's ability to understand, analyze, and control mega infrastructure construction management has been intensified.

However, as noted in this book, the construction of a mega infrastructure project requires complex thinking with respect to the whole as well as the adoption of a comprehensive integrated methodology (Sheng and You 2007; Sheng et al. 2008), whereas technical thinking is merely a part of the complex thinking mode. In addition to technical thinking, the construction of a mega infrastructure construction project requires systematic thinking, humanistic thinking, and creative thinking.

Consequently, in the newly developing world of information technology, which is rife with complex issues, the construction of a mega infrastructure construction project presents several additional requirements (Yang and Zhou 2015):

1. The adoption of an inclusive attitude toward all elements concerning the construction of a mega infrastructure construction project within its life cycle.
2. The effective integration and distribution of all resources necessary for the construction of a mega infrastructure construction project.
3. The integrated use of advanced information and computer technology throughout the construction process.
4. The adoption of various methods and means to develop new and enhance existing construction abilities and, hence, add new value.
5. These various modes of thinking embody a philosophical thinking that incorporates connection, exchange, and integration, namely, Internet Plus thinking.

Under the framework of Internet Plus thinking, all elements of the mega infrastructure construction project can realize the panoramic connection, reconstruction, mining, and cultivation between human and human, human and item, item and item, human and service, human and scenario, human and activity, human and future, reality and reality, and reality and virtuality. The consequence of this is the emergence of a new, more powerful, whole process and the creation of an all-round construction value. This is the critical notion that the current practice of the construction of a mega infrastructure construction project has initially manifested; however, it will spread rapidly, assume a profound revolutionary meaning and exercise significant influence on the construction of mega infrastructure construction projects in the future. Accordingly, it is referred to as *Internet Plus construction of the mega infrastructure construction project* thinking. This formation of this thinking is founded on two points:

1. Modern information and computer technology provide a new and powerful method and tool for managing the challenges arising from the complexity of the construction of mega infrastructure construction projects.
2. The achievement of the Internet Plus construction of the mega infrastructure construction project thinking is a consequence of the current era of the Internet and its infrastructure, at the core of which are the cloud, i.e., cloud computing and Big Data, the network, i.e., the Internet and the Internet of Things, and the end, i.e., the terminal and APP. Together, they create an ecological environment

and platform for the Internet Plus construction of the mega infrastructure construction project.

At this juncture, an important turning point is reached in the evolutionary course of the practices implemented during the construction of the mega infrastructure construction project, that is, from the construction of the mega infrastructure construction project plus internet to the Internet Plus construction of the mega infrastructure construction project. However, this important turning point has resulted in tremendous transformations in the construction of the models of the mega infrastructure construction project. These transformations have led to the new *intelligent construction of the mega infrastructure construction project*.

This type of construction model is labeled intelligent construction for numerous reasons. First, Internet Plus and intelligent interconnection, which have the same core connotation, refer to the formation of a cyber physical system (CPS) combined with three basic elements of the platform type, namely, human society, computer system, and physical world. Once a CPS, as a platform, is combined with mega infrastructure construction projects, it fully manifests the connecting and sharing functions of Big Data. Furthermore, a CPS platform will loosely link the decisions with the main subjects and aspects of the construction project, such as the contractors and suppliers, the physical entity of the construction, the public, and the many value chains of construction, including those related to planning, designing, constructing, operating, and servicing the mega infrastructure construction. The CPS platform makes sensors, embedded terminals, smart devices, intelligent control systems, and communication devices to form an intelligent network via the cyber physical system (CPS) that allows the interconnection between the physical entity of mega infrastructure construction and the construction equipment, among the various smart devices, between the digital world and the physical world and that maintains the continuous exchange of digital information throughout the network.

Thus, the full connection, including the connections between humans, between humans and items, and between the items themselves, has been realized during the construction process of mega infrastructure construction. Via the connection of the Internet, construction equipment builds an integrative information infrastructure of network-cloud-end and stores the data from all aspects of the construction process in the cloud. Hence, these data are available throughout the construction process.

As a consequence, the entire building process of the mega infrastructure construction will do the following:

1. Realize the intelligent construction process via connections between construction smart devices and intranet interconnections of construction projects.
2. Integrate upstream and downstream industrial chains to create a more intelligent construction via the collaborative network.
3. Extend the individualization and servitization to realize the combination of the physical entity and the network virtuality.

In other words, the CPS exhibits relatively advanced intelligent behaviors and capabilities that are, to some extent, similar to the human brain in the complicated and unknown construction environment of the mega infrastructure construction project. For example, the CPS has the ability to automatically obtain and apply knowledge about construction given certain thinking processes and logical reasoning and to analyze and solve on-site construction issues by applying automatic learning. That is, the CPS mimics human intelligence to some degree, and therefore, people call the core of this type of construction model revolution intelligent construction.

Obviously, intelligence, as discussed here, is a type of intelligence that is, in some ways, similar to the human intellect, as reflected by the artificial CPS platform. In essence, the CPS and other modern information technology platforms provide a simulation of man's information processing of human awareness and thinking rather than an actual demonstration of man's intelligence. In other words, the CPS thinks and acts, to some extent, as humans do. Consequently, intelligence, as used herein, is the intelligence function that is represented by the CPS.

However, it is because of this that the level of intelligence as demonstrated in the building process of construction cannot be compared with actual human intelligence. Furthermore, it cannot attain the level of self-adaptability and self-organization that is expressed by humans through their personal recognition, learning, reasoning, and judgment when confronted with the various complexities of the construction process of the mega infrastructure construction project.

It is necessary to consider that the current concept of intelligence is also prevalent in the manufacturing of modern factories. The environments of the Internet and Big Data have already resulted in the formation of different types of intelligent manufacturing models for plants, and, as a result, they have promoted the automatic and intelligent unmanned factory. This is primarily because, for those mass-production-manufacturing factories that emphasize standardization and routinization, human intelligence, abilities, and knowledge about product manufacturing can be embedded into the products' manufacturing technology and processes through standard programs and rules by establishing an ideal enclosed environment that depends on the accuracy of the automated equipment. In this sense, a human is no longer needed on site during the normal process of product manufacturing.

That said, the construction scenario of a mega infrastructure construction project is quite different. Even though the first-phase decisions and plans regarding the mega infrastructure construction have been finalized, there are three factors that must be managed during the process of construction. First, various uncertainties and emergencies that require the immediate response of the main subjects of the construction project may occur at any time on a highly open and complicated construction site. Second, although many complicated on-site issues have clear and scientific explanations, techniques and technological principles are still necessary to depend on on-site experience, comprehension, intelligence, intuition, and perception to resolve those problems. More importantly, these special abilities are the result of man's advanced intelligence. Third, in addition to the construction of the main body's technological capabilities, construction building also includes human emotions, cultures, perceptions values, none of which can be easily replaced by artificial intelligence.

These demonstrate not only that it is impossible for the intelligent construction of the mega infrastructure construction project to become absolutely unmanned, as with the intelligent manufacturing by factories, but that man's intelligence is always the most important and dominant factor. In other words, artificial intelligence merely complements and supports human intelligence.

In brief, the intelligent construction of the mega infrastructure construction project is always centered on man's intelligence and supplemented by artificial intelligence. That is, artificial intelligence can only add to man's relatively basic and simple intelligent functions during the intelligent construction process, whereas man's more advanced and complicated intelligent functions require additional human skills and knowledge. Therefore, not all functions and responsibilities related to the construction of a mega infrastructure construction project can be relegated to a CPS or a robot.

10.4 Intelligent Management of Mega Infrastructure Construction

The intelligent construction model of mega infrastructure construction based on the CPS platform will naturally promote corresponding transformations of the management model. *We call this type of management model of mega infrastructure construction, which corresponds to the intelligent construction model of mega infrastructure construction, the intelligent management of mega infrastructure construction.*

As the intelligent construction model of mega infrastructure construction has only recently been formed, the corresponding intelligent management practice is in a nascent stage and still under exploration. Thus, at the present time, the perspective of Big Data and the Internet-driven environment can be defined, and the basic principles of mega infrastructure construction management can be integrated to conduct the framework design and prospects of mega infrastructure intelligent management according to the basic connotations and features of the intelligent construction of the mega infrastructure construction project. However, as the intelligent construction practice of the mega infrastructure construction project is continuously enriched and developed, the intelligent management activities are also gradually enriched and developed.

To more easily comprehend the intelligent management of mega infrastructure construction, a framework of descriptions is provided:

1. Change in the core thinking of the intelligent management of mega infrastructure construction

The core thinking of the intelligent management of mega infrastructure construction is a comprehensive thinking. As such, it recombines the site, overall situation, industry, and environment of mega infrastructure construction to form a network of complex systems that are closely related to and nested near each other. Furthermore, through the exchange, connection, and integration of information and data, core thinking achieves the construction and intelligent management of mega infrastructure construction, as illustrated in Fig. 10.2.

At the core of intelligent construction is the use of information technology and the application on the CPS platform of the intelligent functions of the subjects during construction projects. Correspondingly, to improve management levels and capabilities, intelligent management requires the use of information technology to create intelligent management functions that are similar to those that humans conduct during management activities. Data play a vital role in intelligent construction, and similarly, data play an important role in intelligent management. In a certain sense, the essence of intelligent construction is data construction. Similarly, the essence of intelligent management is data management.

Thus, a fully functioning data center that includes the collection, storage, processing, analysis, integration, mining, and management of data is important for the intelligent management of mega infrastructure construction.

2. Change in the organizational pattern of the intelligent management of mega infrastructure construction

Modern information technology, including the Internet, the Internet of Things, cloud computing, and mobile intelligent terminals in the intelligent construction pattern of mega infrastructure construction, is likely to produce technology,

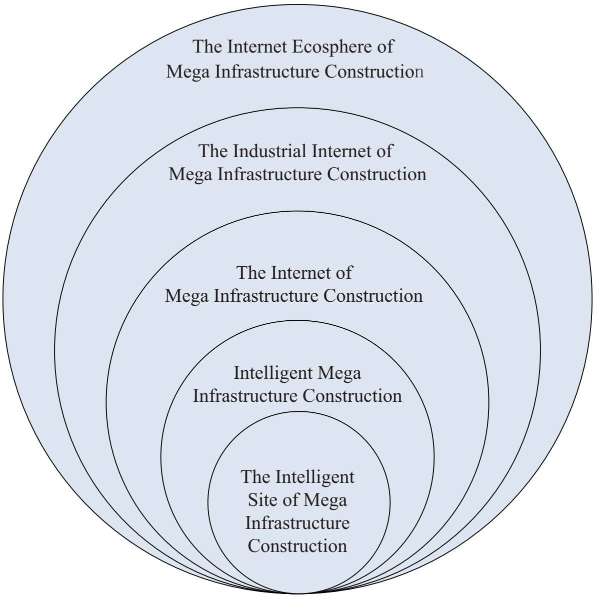

Fig. 10.2 The core thinking of intelligent management of mega infrastructure construction

networks, and data and hence become a new element in the force system for the organization's subject of the intelligent management of mega infrastructure construction. Accordingly, this will alter the original pattern of the force system of the intelligent management organization, establish a new organizational pattern for the intelligent management of mega infrastructure construction, and prompt the emergence of new organizational functions and behaviors. Currently, a type of organization and behavior in coordination with the network tends to appear among the core subject, contractors, suppliers, financial institutions, consulting firms, and other professional organizations and stakeholders in the organization of the intelligent management of mega infrastructure construction. Moreover, there may appear a complex network mode that is subject to flattening and flexibility, characterized by the coexistence of a dominant core subject and decentralization, strongly associated in the transverse direction, and linked by the hierarchical principal-agent relationship (Zhang and Sheng 2014). *In addition to the traditional management and control, service for the whole process of intelligent construction will be added to the functions of intelligent management organizations.*

3. Change in the intelligent decision-making management of mega infrastructure construction

In the pattern of intelligent management of mega infrastructure construction, data play a role of unprecedented importance in the decision-making process. For example, the Internet and the analysis of public sentiment strengthen the exchange between the main decision-making body and the public. However, the CPS enables the decision-making activities related to mega infrastructure construction to interact with each other during the whole processes including definition of decision problems, design, selection, and evaluation of the decision-making scheme on the platform during the analysis of Big Data throughout the entire construction process. This is a major change in the decision paradigm of intelligent management of mega infrastructure construction in that the decision platform can accomplish granular scaling, trans-boundary associations, and panoramic visualization of decision problems (Wang et al. 2016). This is closely related to the basic concepts of multi-scale adaptation and the spectrum function as well as specific principles of the management theory of mega infrastructure construction, such as complexity degradation, adaptive selection, multi-scale management, and iterative generation. In other words, the pattern of intelligent management facilitates the establishment of a multistage, multi-level, multi-scale, distributed, panoramic decision pattern for mega infrastructure construction and the development of a decision-aided analysis method for the automatic promotion of decision-making knowledge. Ultimately, the computing of Big Data will be transformed into the calculation of the decision-making subject, which, in turn, will reinforce the subject's wisdom during the decision-making process.

4. Change in the intelligent quality management of mega infrastructure construction

The intelligent management of mega infrastructure construction is more conducive to employing new information technology to achieve overall quality durability

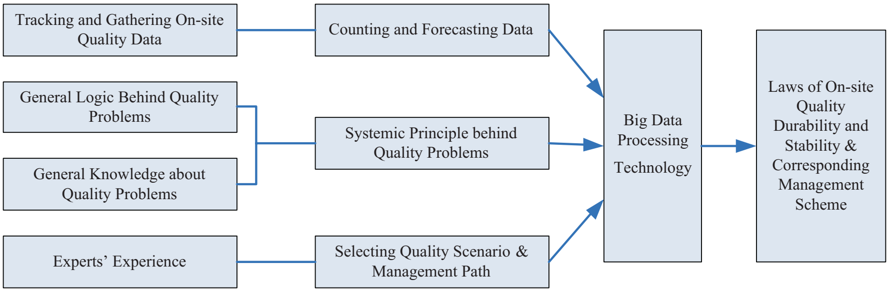

Fig. 10.3 The intelligent quality management path of mega infrastructure construction

and quality stability at the micro level for mega infrastructure construction. Moreover, the on-site management of mega infrastructure construction is a type of multi-objective, coordinated management with quality as its kernel. In this sense, it is conducive to forming a total-factor management path for quality management, as presented in Fig. 10.3.

Furthermore, through on-site quality monitoring and platform control, which includes the monitoring of the environment, an early warning system, an on-site supervision system, a communication system, a health monitoring system for construction structure, a computer-based virtual reality system, etc., it is feasible to conduct a research of accurate quality management at a more granular level. The areas to be researched at this level would include the transmission path, the law of on-site quality fluctuation, incentives, thresholds, quality control technology, precautionary measures, as well as a disaster analysis of quality variation.

5. Change in the intelligent safety management of mega infrastructure construction

First, we should establish an equipment database that includes information about equipment types, requirements, operations, and malfunctions for the on-site equipment of mega infrastructure construction. The behavioral habits and behavioral preferences of individuals should be considered when establishing a database of safe behaviors for on-site personnel. Furthermore, a database of safety cases based on domestic and foreign materials and information about mega infrastructure construction accidents and events should be created. Then, using these databases of safety cases, behaviors, and equipment, an integrated database regarding intelligent safety management with respect to mega infrastructure construction can be developed by exploiting Big Data, cloud computing, and other technologies.

According to the concept of the Internet of Things, on-site situations can be monitored, and machine-learning methods that correlate with construction methods, human behaviors, and on-site environments to predict security accident levels can be applied, thus allowing for real-time pre-warnings and predictions about on-site unsafe conditions and behaviors.

Safe actions can be perceived based on the safe behavior patterns of the individual. By considering the interactive coupling of people's behaviors, technologies, and environmental changes, the causes of and reasons for accidents can be determined.

Moreover, the safety adaptability of construction schemes can be evaluated through situation simulation, which can enhance the ability to make accurate predictions about the safety risks related to mega infrastructure construction.

Moreover, the BIM, various safety situation simulations can be conducted during the construction process of a mega infrastructure construction project, such as simulations of accident treatment plans for escaping or evacuating areas, emergency plans, etc., to identify possible safety risks and correct them.

6. Change in the intelligent supply chain management of mega infrastructure construction

The intelligent management of mega infrastructure construction can exploit support from the Internet environment of the mega infrastructure construction industries and Big Data technologies and apply it to the on-site supply chain management of mega infrastructure construction. This application is a deep revolution that integrates computer technology and the on-site supply chain management of mega infrastructure construction at the level of "intelligence," thus forming intelligent supply chain management. More specifically, first, intelligent supply chain management forms an interindustrial, interdepartmental, and interregional production system for mega infrastructure construction industries. This chain, which includes governments, project companies, suppliers, and contractors, is based on the Internet of Things and the Internet. Second, the supply chain forms an information and data embedded system for purchasing and supplying key goods, such as materials, equipment, and components. Then, according to the materials and information needed throughout the entire on-site construction supply chain and the complete life cycle of the construction, the chain can realize the supply source of on-site construction materials and components. Third, intelligent supply chain management forms a good early warning system that runs through all parts of the supply chain, including all main bodies and all levels, with the aim to make the continuous supply chain activities quality stable and cost controllable and to realize the real-time management of distributed supply chains, risk monitoring, and management. Fourth, supply chain management can realize real-time management, maintenance, and workload and provide early warnings of on-site equipment faults and conditions as well as conduct remote diagnoses of key equipment. In addition, it can complete a fault analysis based on industrial Big Data and provide maintenance and other services accordingly.

10.5 Theories About Intelligent Management of Mega Infrastructure Construction

The changes identified herein are basic ones produced by the intelligent construction model of mega infrastructure construction in management thinking, behaviors, and activities. The fields where these changes may occur are, in effect, far more and profound than that. In particular, changes of overall and radical significance will not only touch upon the technology for mega infrastructure construction management, but they will also profoundly influence the form of management activities in mega infrastructure construction as well as people's theoretical thinking. Hence, the following two tasks deserve attention:

1. At the level of theoretical thinking, it is necessary to consider what new theoretical elements regarding the intelligent construction of mega infrastructure construction will be produced by the practical changes in construction management. These elements will either enrich the meanings of original concepts, principles, and scientific issues of the former theoretical system or further expand the former theoretical system, which will result in new fundamental concepts, principles, and scientific issues.

It is noted that, at least for the near future, intelligent management thinking is unable to subvert the fundamental theoretical system of mega infrastructure construction management founded on the complexity of thinking. However, it is highly likely that intelligent management thinking will enrich, expand, and correct the concrete forms, structures, and connotations of certain principles and scientific issues of the former theoretical system, which is perceived as a positive development.

2. At the level of construction thinking, the transformation from the technical thinking of mega infrastructure construction plus Internet into the complex entirety thinking of Internet Plus mega infrastructure construction is a critical representation of the unceasing progress and development of the practice and theory of mega infrastructure construction management. Therefore, we reflect on how to achieve this transformation as soon as possible. For example, it is feasible:

   – To design the Internet index of mega infrastructure construction or the intelligent construction index of mega infrastructure construction based on Internet technologies to measure mega infrastructure construction
   – To devise the strategic plans and road maps for Internet Plus mega infrastructure construction or intelligent construction of mega infrastructure construction at different levels
   – To research the theories regarding the intelligent construction of mega infrastructure construction projects, develop core technologies and equipment, conduct a pilot study on key intelligent construction, promote the industrial Internet plan of mega infrastructure construction, etc.
   – To focus on developing Big Data and a cloud computing network for mega infrastructure construction, the Big Data technology for the analog machine of digital construction, the technology for the overall intelligent control and analog simulation of mega infrastructure construction, etc.

In summary, two possible paths to the continuous development of the theoretical system of mega infrastructure construction management have been advanced at the overall level of theoretical innovation. One is the direct formulation of a new theoretical innovation consistent with the premise of a logical sequence of thought regarding the complexity of the system's theoretical essence. The other involves the scenario linking the current developments in technology with the practice of mega infrastructure construction. However, due to the addition of the Internet of Behaviors, the Internet of Things, the Internet of Measurement, the Internet of Detection, the Internet of Services, and other information platforms based on statistical science and cloud computing and the support of multifunctional, multi-scaled, and multi-granular federated models, the physical complexity, network complexity, and systematic complexity present a significant increase in the construction processes and management activities of mega infrastructure construction.

To sum up, either one of the two paths or a combination of the two paths will facilitate the further expanding and deepening of mega infrastructure construction management theories and the formation of theoretical innovations. Meanwhile, these paths also serve as a powerful motivator for the development of theoretical innovations with respect to mega infrastructure construction intelligent management.

We must acknowledge that due to the limitations of the two points of practice and our understanding, more detailed and more accurate constructions or descriptions about theoretical systems of intelligent management of mega infrastructure construction could not be derived. Thus, these constructions will become the outcome of the continuous abundance of intelligent management practice of mega infrastructure construction in the future, which is also an inevitable trend. Therefore, the sensibility of the academic world can facilitate the understanding that the intelligent construction of mega infrastructure construction project will not only lead to great revolutions in intelligent management activities of mega infrastructure construction but also promote further theoretical innovations of intelligent management of mega infrastructure construction. Thus, profound thinking and positive explorations regarding this theoretical innovation under the guidance of meta-synthesis methodology should be conducted.

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Main Theories in Part 4

After the initial construction of issues regarding the basic concepts, i.e., the basic principles and scientific problems of the mega infrastructure construction management theoretical system, the new principles and system of research methods are designed according to the unique essential attributes of each research object, which should also become an essential part of the theoretical system.

To be specific, a comprehensive integration methodology that combines reductionism and holism fully embodies the integrity of mega infrastructure construction management activities and the complexity of management issues, and as such, it becomes the principle of the mega infrastructure construction management theoretical research method system.

Furthermore, three types of new key methods are proposed:

1. In view of the characteristics of the complex integrity of mega infrastructure construction management activities and issues, beginning with the complete scenario (background) of management activities and issues, the inherent relationship and formation mechanism between macro phenomenon and micro behavior should be deeply explored, and its universal law or nature should be revealed through systematic analysis, i.e., a panoramic qualitative analysis method.
2. Because the concept of scenario fully embodies the complex integrity of mega infrastructure construction management and is closely related to the quality evaluation of the mega infrastructure construction deep uncertainty policy and because the specific mega infrastructure construction management activities generally belong to the small sample, the reconstruction, discovery, and prediction method of construction management scene becomes the common key method, which is an effective method that is rarely found in traditional research methods. As a result, the scenario cultivation method is proposed to solve this difficulty.
3. As mega infrastructure construction management encompasses complex integrity, its issues embody the physical, virtual, and informational worlds of construction; relate to people, things, and events; and involve multiple fields, disciplines, levels, dimensions, and scales. Therefore, it is necessary to consider

all of the previously mentioned research platforms. The mega infrastructure construction management federation modeling method, which is mentioned for the first time in this chapter, belongs to such a platform. This platform consists of the complex integrity of mega infrastructure construction management activities at the global level as well as at the whole process level and the whole staff level, which is dependent on the environment and conditions of the platform's complete function. This platform embodies core technology routes of metasynthetic thought based on qualitative, quantitative, and combined simulation experiments, human-computer combinations and human dominance. Furthermore, as it fully acknowledges and promotes the advantages of advanced information technology and exhibits a strong platform function, this platform is advanced in the field of academia.

Postscript

On the basis of practical cognition and theoretical consideration of China's mega infrastructure construction management spanning three decades, I spent an additional 3 years organizing and constructing the information and data necessary to create this book. My consistent pursuit of exploring mega infrastructure construction management theory has always been the primary motivation to accomplish this task.

Explicit vision, accurate definitions, complete structure, and clear academic thought did not immediately arrive during the initial exploration of the theory (system). In contrast, many problems appeared vague, erratic, and even conflicted with each other. Thus, the most important task was to establish the goal of theory research and the core of analysis, namely, to establish the principle of theoretical thinking and the epistemology and methodology of the theoretical system and to further optimize the system and logic. All of these elements, however, experience an ever-maturing process.

The exploration of a theory (system) is a convoluted process. As is often the case, during the exploration process, the thinking path is broken. Therefore, a calm mind must be maintained and must persevere on the new road to exploration. When research reaches an impasse, the only power encouraging continuation is one's dedication to theoretical exploration. Even research can become boring and monotonous, but as long as an original explorative interest remains, new ideas will emerge and inject new enthusiasm into the research much like spring bringing life to a stagnant winter. Furthermore, sound theory cannot be accomplished by action alone. Rather, it must experience detention and retrospection, just as the best runners must experience a bottlenecking stage to break through limitations of the body. In this sense, thoughts and physical fitness are the same.

A Chinese idiom, casting a brick to attract jade, means to throw a brick of clay in exchange for a piece of jade offered by someone else. In other words, one should repress the drawing forth of attractively alluring ideas with personal half-baked notions. This is the attitude the author holds in the face of critical scientific problems

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such as the mega infrastructure construction management theory. While this work is limited to immature and imperfect academic insight when considering grand and complex scientific problems and the limit of individual abilities, much like the brick, it will arouse the interest of everyone to further develop open and honest communication and cooperation in an effort to form numerous academic perspectives, much like the jade, and through these collaborative efforts to ultimately achieve progress in the development of the mega infrastructure construction management theory. This should be the common attitude and desire.

While there are still deficiencies and regrets in both the overall structure and details of the book in the face of such a complex and grand theory research subject, individual ability, level, practice, and time are always too limited to create a comprehensive and delicate theory. Mega infrastructure construction management practice is always in development, and corresponding construction management theory has also been sublimated. This book strives to provide the opening topics of theory innovation for scholars to further study and enhance the base possibilities of space in the future.

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