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RESEARCH ARTICLE

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Meta-synthesis management framework of a complex project: A case study of the deck pavement project of the Hong Kong-Zhuhai-Macao Bridge

Abstract Innovative technology and deep uncertainty during the design and construction process of complex projects introduce great challenges to their organization and management. The traditional methods, represented in the project management body of knowledge (PMBOK) guide, can solve systematic problems; however, they cannot solve complex problems. Based on the management practice implemented in the deck pavement project of the Hong Kong-Zhuhai-Macao Bridge (HZMB), in this work, we propose a meta-synthesis management framework for a complex project from the perspective of the science of complexity. The method deems that the complexity of the project has the characteristic of being multi-scale both in the design phase and the construction phase. These problems can be classified into different categories, each of which requires a different strategy. As a result, it is first necessary to adopt the "exploration" strategy to reduce project complexity and to transform the deep uncertainty problems into systematic problems. Then, the "exploitation" strategy should be used to apply the PMBOK and other traditional methods to achieve the design and construction goals of the project and to improve its efficiency. More specifically, in the design phase of a complex project, the "innovative integration" process is used for the exploration of the new engineering technology and knowledge; then, the "functional integration" process is employed to define the system architecture, the interface relationship, the technical index, and other functions. In the construction phase, the "adaptive integration" process is used for the construction of the engineering organization system; next, the "efficient integration" process is employed to improve the actual construction performance. The meta-synthesis management framework proposed in this work reveals the multi-scale principle of solving complex problems in the management practice of a complex project, and develops the methodology of meta-synthesis.

Keywords complex project, meta-synthesis management, Hong Kong-Zhuhai-Macao Bridge, exploration strategy, exploitation strategy

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1 Introduction

Complex projects typically have complexity characteristics, such as long lifecycle, large scale, highly innovative technologies, and several uncertain factors; therefore, they are difficult to manage (Scott et al., 2011). Although several methods are employed in this type of projects, most complex projects are behind schedule, over the budget, and fail to achieve their original objectives (Flyvbjerg et al., 2003). Traditional project management methods, such as time, cost, scope, and risk management proposed in the project management body of knowledge (PMBOK) (Drob and Zichil, 2013), divide the entire management process into different types of knowledge, which can solve certain systematic problems with weak correlation and uncertainty; however, they cannot solve complex problems (Saynisch, 2010). Under the basic assumption that general reductionism cannot solve the problems of complexity, the meta-synthesis management method proposed by Chinese scholars has introduced a new methodology with a holistic perspective for the solution of complex problems, and has already been well applied in several engineering fields (Gu, 2015; Davis and Mackenzie, 2014; Davies et al., 2009; Chen and Chen, 2014; Chai and Sun, 2016).

Currently, the meta-synthesis management method is still evolving. First, meta-synthesis is still a methodology based on holism, which needs to be materialized as a project management method through its combination with project management practice. Second, the meta-synthesis management method needs to be integrated with traditional project management methods. This means that the complex problems of a complex project need to be considered on the basis of systematic understanding; a feasible manner to achieve this is to transform complex problems into systematic problems, which can then be solved through project management methods. Third, contemporary research works on meta-synthesis have been focused only on the design phase. There is still an insufficient number of research works on the meta-synthesis strategic path for the construction phase. Therefore, the meta-synthesis management method needs to be further expanded in terms of the theoretical content, the coverage of the life cycle of the project, and the strategic path.

The project management practice of the Hong Kong-Zhuhai-Macao Bridge (HZMB) offers itself as a good case and an opportunity for us to summarize and refine the meta-synthesis management method because, first, the HZMB is a typical complex project with complexity characteristics. Second, the project managers — under the guidance of the concept of meta-synthesis — have adopted a number of innovative manners of management to address the complexity of the HZMB. Third, the design, construction, and management companies of the HZMB are all leading companies in the field of engineering in China, and have rich experience in traditional project management methods. This fact provides a good contrastive case for us to study how to transform complex problems into systematic problems.

According to the case study of the management practice of the HZMB, in this study, we propose a meta-synthesis management framework for a complex project. The framework deems that, both in the design phase and the construction phase, the "exploration" strategy is required to be first adopted in order to transform deep-uncertainty problems into systematic problems. Then, the "exploitation" strategy is needed in order to achieve the design and construction objectives through the implementation PMBOK and other methods. Moreover, in the design phase of a complex project, the "exploration" strategy refers to "innovative integration" and the "exploitation" strategy refers to "functional integration;" in the construction phase, the "exploration" strategy refers to "adaptive integration," whereas the "exploitation" strategy refers to "efficient integration."

The present work is structured as follows. In Section 2, a review of the relevant literature will be presented; in Section 3, the research methods will be described and the basic case study will be introduced. In Section 4, the complexity characteristics of the HZMB deck pavement will be analyzed. Next, in Section 5, the meta-synthesis management framework for a complex project and its practical application in the management of the HZMB will be presented. Finally, the concluding section will provide a summary of the present study.

2 Literature review

In general, integration refers to the combination of two or more elements into an organic whole according to certain rules in order to realize an entire function (Morris, 2013; Chang et al., 2013). Based on the nature of the elements and the correlation between them, the organization, control, management, and integration processes are all different from one another. In the field of complex project management, the current theories on integration research can be divided into the following two types.

One type of integration research is referred to as system integration research. This type of research focuses on the systematic nature of the integrated objects, and considers that the interface between the subsystems can be clearly understood through a good system design. The task of the construction phase is to combine this structured system in an effective manner (Halfawy and Froese, 2007). Philbin (2015) proposed an integrated system, which included the process, technology, resource, knowledge, culture, and impact of technology. Liu et al. (2014) identified certain critical success factors for innovation in the construction phase from the perspective of integration. This type of research suggests that project management could render the entire integration process more effective through planning, control, and coordination, and that the computer-integrated manufacturing system (CMS) method — which has been adopted in large-scale production processes — is always used for the realization of technology (Boddy et al., 2007).

The other type of research is referred to as meta-synthesis. This type of research focuses on the complex problems of projects, where uncertainty and interdependency are considered as the main challenges for the management of the project. First, uncertainty is associated with the introduction of new engineering techniques or innovative engineering subsystems. Because of the innovation, the interfaces between the subsystems are not clear; even a certain interdependency relationship in the design process itself is a problem (Shenhar, 1993; Shenhar, 2001); Second, owing to the interdependency between the subsystems of the complex projects, the problems that arise during the construction of the subsystem will lead to changes in other subsystems; this will affect the original integration plan as well, thus resulting in uncertainty (Locatelli and Mancini, 2010; Salet et al., 2013); Third, external environmental changes, such as supplier changes and financing problems, can cause unpredictable events, which can interfere with the original integration process as well (Geraldi et al., 2011; Scott et al., 2011).

For this type of complex problems, researchers have proposed integration methods of higher levels. Davies and Mackenzie (2014) divided integration into two types: meta systems integration and system integration. The meta systems integration would be employed for the integration of systems, whereas system integration would be employed for the integration of subsystems. The authors recommended that management rules be established to respond dynamically to uncertain and changing conditions. Davies et al. (2009) believed that the knowledge and experience from other fields could improve the performance of a complex project in the design and the construction phase, and proposed an integration framework and its processes from the perspective of innovation. In China, Qian et al. (1990) put forward a meta-synthesis methodology, combining the expert system, data, the information system, and the computer system to compose a highly intelligent combination of man-machine, human-network integration system (Yu, 2001). Certain scholars applied this methodology to different fields, such as weapons system demonstration and the development of a socio-economic system reform program (Yu and Tu, 2002; Yu and Zhou, 2005); other scholars actively explored the development of the methodology, proposed a technical route to build the seminar of meta-synthesis based on the Internet technology (Dai and Cao, 2002), the meta-synthesis knowledge system (Gu and Tang, 2002). Furthermore, certain scholars explored the application of this methodology to the management of complex projects. For example, Sheng et al. (2008), Liang and Sheng (2015) proposed a meta-synthesis management method and explored its principles, paradigms, functions, and applications for complex projects. Xu and Lu (2009) proposed a meta-synthesis assessment system of "man-machine-method-technology-data," and applied it to the assessment of an earthquake disaster. Chen and Chen (2014) proposed a multi-dimensional meta-synthesis framework, which included the objective, the organization, the process, and other elements from the perspective of sustainability for an urban complex project. Chai and Sun (2016) thought that meta-synthesis could integrate different systems to realize the function of the entire project.

The aforementioned research works have provided good concepts for the meta-synthesis of complex projects; however, certain problems exist, which will be described in the following.

First, both the system integration and the meta-synthesis management method reflect only one side of the complex projects. As a high-level method, the meta-synthesis of complex projects should solve the systematic problems, as well as the complex problems. Therefore, the two aforementioned methods should be integrated and unified (Hong et al., 2010).

Second, meta-synthesis is a methodology, which needs to be solidified in order for a specific management theory to be proposed based on project practice. Meta-synthesis only focuses on the decision making that pertains to the design and management methods at the design phase, without considering the meta-synthesis problem of the construction phase. The meta-synthesis management method should be expended to cover the entire life cycle of the complex project.

Third, thus far, no meta-synthesis management method has been developed for complex projects that would be able to summarize the management practices and to describe different integration strategies and integration processes in detail.

In view of the aforementioned problems, in this work, we will propose a new meta-synthesis management framework through the case study of the HZMB, and will summarize its successful implementation.

3 Research methods

Although the deck pavement is a part of the HZMB project, it is a typical complex project; moreover, its design and construction highlight the complexity of complex projects (Gao et al., 2016).

First, the deck pavement project of the HZMB is substantially large. The total pavement area is 700000 m^2 which is equivalent to 98 standard football fields. In the project, the pavement of the steel box girder bridge is 200000 m^2 and the pavement of the combined beam bridge is 200000 m^2.

Second, the structural standards for the deck pavement of the HZMB are very high. According to the project requirements, the life of the asphalt concrete pavement of the HZMB is planned to reach 15 years, which is 3 times higher than the ordinary highway pavement life.

Third, the deck pavement technology of the HZMB is an innovative project. Although China has nearly 20 years of experience in the construction of long-span steel box girder bridges, the steel deck pavement problem has not yet been effectively resolved. To clarify the technical terms, the steel box girder is a large thin-walled space structure. Under the condition of being fully loaded, it will become elongated, shortened, bent, and twisted. The deck pavement must possess the ability to simultaneously follow the deformation of the steel box girders. On the other hand, the deck pavement directly bears the wheel rolling load; therefore, the deck pavement needs to resist the local deformation of the wheel load, while maintaining a smooth surface for purposes of safe and comfortable driving. This contradictory demand determines the complexity of the pavement engineering technology of a steel deck.

In summary, the deck pavement project of the HZMB offers itself as a good case study, and it meets standards of the single case study of Yin (2013) and those of the formation theory.

Data from the case study have been collected from 2015 to 2017. We interviewed 20 engineering staff at all levels, including the senior managers of the HZMB Authority, the project contractors, the project supervisors, and the project construction workers. Furthermore, we collected the management documents, related contracts, engineering reports, and news materials on this project.

4 Classification of complex problems of a complex project

The problems faced in the design and the construction process of a complex project are multi-scale; this means that these problems present great differences in importance, relevance, hierarchy, time, and space (Sheng, 2017). According to their characteristics, these problems can be divided into two types. One type refers to systematic problems, which bear the following characteristics: the design and construction technology is mature, the interface between the subsystems is clear, knowledge on how to decompose the entirety into subsystems exists, the manner in which the subsystems should be connected and integrated to the upper system is already known, and the components used have been verified in several other projects. The other type refers to complex problems, which bear the following characteristics: the technical methods of construction and organization management have not yet been mastered, the interface between the subsystems is not clear, the knowledge on system decomposition and integration is fuzzy, and the components used are completely new. Based on its nature, the former class of problems is a definite problem or a general uncertainty problem, which can be described by means of the probability theory, whereas the latter is a class of deep uncertainty problems, the results of which cannot be described by means of the probability theory because of nonlinear interdependency, and the evolution process mechanism of which is still unknown. Table 1 summarizes the two types of different problems in a complex project and the characteristics thereof.

In the deck pavement project of the HZMB, the project design phase and the construction phase encompass different complex problems and systematic problems, as listed in Table 2.

5 Meta-synthesis management framework and its process

5.1 Meta-synthesis management framework of complex projects

Hobday et al. (2005) considered that the integration strategy is necessary both in the design phase and the construction phase. Because of the different characteristics of complex and systematic problems in the design and the construction phase of complex projects, the meta-synthesis management framework has different strategies and processes for different problems and different phases.

5.1.1 "Exploration" strategy

For a complex problem, its construction technology and management knowledge are normally not available or mature; therefore, the nature of this type of problems is that of deep uncertainty. Faced with deep uncertainty, the primary task of meta-synthesis is to efficiently reduce the complexity of the project and to explore new engineering technologies and management methods. In this process, the project agent should continuously acquire the knowledge, accumulate the engineering experience, and enhance the adaptability. This is an expansion process in terms of acquiring new knowledge and new abilities; therefore, we regard the meta-synthesis management framework that focuses on problems of complexity as the "exploration" strategy. Through "exploration," the com-

Table 1 Problems and their characteristics in a complex project

Type	Technology	Interface	Information	Experience	Uncertainty
Complexity problems	Immature	Relationship is unclear	Ambiguity, lack of knowledge	No	Deep uncertainty
Systematic problems	Mature	Relationship is clear	Accuracy, sufficient knowledge	Yes	Definite and general uncertainty

Table 2 Engineering problems in the deck pavement project of the HZMB

Type	Design phase	Construction phase
Complex problems	Technological options of bridge deck pavement, aggregate requirements	Contractor selection, contractor organization and management, factorial production of aggregate
Systematic problems	Function requirements for rust prevention, spray requirements for waterproofing the bridge	Manufacturing, selection, organization, and management of rust and spray equipment

plex problem can be transformed into a systematic problem.

At the same time, because complex problems have different features at different stages of the project, the integrated process presents different characteristics as well. In the design phase, the complexity is mainly manifested in the complexity of cognitive (Howell et al., 2010). More specifically, because the technical solution is unknown, we need to "explore" new technical knowledge through innovation and creation. Here, the "exploration" strategy can be expressed as the "innovative integration." Furthermore, in the construction phase, the complexity is mainly manifested in the associated structure of the project organization and the uncertainty of the construction process (Salet et al., 2013). To address this problem, dynamic ability is needed for stability and change in complex, uncertain, and volatile project environments (Davies et al., 2010; Davies and Brady, 2016; Davies et al., 2016). It's needed to find the appropriate construction companies and to organize them into a flexible organization to burden the various risks during construction. In this phase, the "exploration" strategy can be expressed as "adaptive integration."

Consequently, we can define the "exploration" strategy as the process of exploring innovative engineering technologies, methods, and the adaptive organization through the integration of new elements. Therefore, in order to realize the objectives of the complex project, the involved agencies should adopt innovative technologies and acquire new engineering knowledge through "innovative integration" processes — such as collaborative innovation and the introduction of technology in the design phase — and they should set up adaptive organization by integrating more suitable and capable agencies in the construction phase.

5.1.2 "Exploitation" strategy

With regard to systematic problems, because of the relatively mature technology and rich management experience, the primary concern is to determine the specific technical standards, and to then accomplish them through optimization, control, and lean management; in addition, the system engineering and project management can be used as integration methods for this type of problems. The system engineering can define the interfaces between the subsystems, and the project management can render the integration process well organized and planned (Sapolsky 2003; Johnson, 2003). Currently, the goal of meta-synthesis is to fully expand the existing knowledge and experience and to improve the performance of the project on the basis of achieving its basic functions. Therefore, the integration process that focuses on the certain problems will be referred to as "exploitation" strategy.

Similarly, owing to the fact that the characteristics of systematic problems vary at different stages of the project, their integration process is different as well. In the design phase, the technical solutions have been identified, and the systematic problems are manifested as the detailed compilation of the relevant technical indicators and the exact definition of the project functions. In this phase, the "exploitation" strategy can be expressed as "functional integration." In the construction phase, the systematic problem is the validity of the construction process, and it is necessary to realize the technical objectives and the system function through appropriate project tools and advanced management. Therefore, the "exploitation" strategy can be expressed as "efficient integration."

Similar to the definition of the "exploration" strategy, we can define the "exploitation" strategy as the process of defining and illustrating in detail the system structure of an engineering project, as well as the technical specifications and management rules, through the integration of conversant elements. Therefore, in order to efficiently realize the objectives of a complex project, the involved agencies should define the structure of the engineering system precisely, allocate the technical index to an appropriate agency accurately through "functional integration" processes, such as interface definition and function combination in the design phase, set up specific management rules, and adopt lean construction management in the construction phase.

Figure 1 describes the two different integration strategies for different problems and the integration processes in different phases.

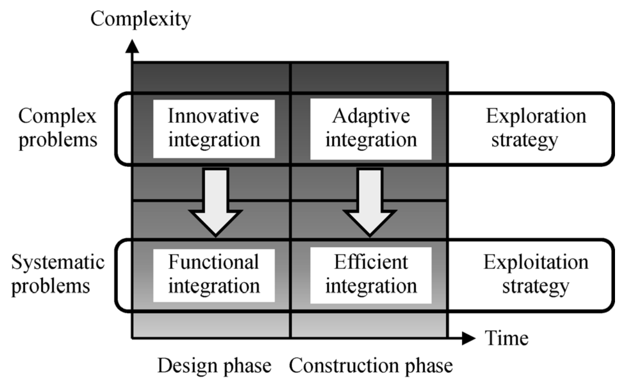

Fig. 1 Meta-synthesis management framework of complex projects

From the perspective of integration, the "exploration strategy" aims to ensure that the structure of the engineering project will be properly defined, and the "exploitation strategy" aims to optimize and improve the integrated system.

5.2 Meta-synthesis process of the design phase

In the design phase of a complex project, the "innovative integration" of the "exploration" strategy is employed to solve the problem of cognitive complexity through innovative engineering knowledge and technical methods. The "functional integration" of the "exploitation" strategy is employed to define the technical index, the system interface, and other functions of the subsystems.

5.2.1 Innovative integration

In the phase of the project design, the complexity of the problem is mainly cognitive complexity; that is, we are unaware of the types of technical solutions that should be used to achieve the high objectives of a complex project (Howell et al., 2010). Because of the innovation of a complex project, the engineering technology program, the development of equipment tools, and the management methods are ambiguous; they may even be unknown. It is difficult to exactly determine the structure and the interdependency of the systems through the "decomposition" approach; hence, there are complex problems in terms of system cognition for both the design and the construction units. For such complex problems, there is no mature knowledge on the design and the construction, and previous management methods are no longer effective; thus, there is an imperative need for the development and accumulation of new knowledge. On the one hand, based on the objectives of the project, the relevant units need to constantly explore technologies and management methods in various manners — such as the joint development, the introduction-digestion-innovation, computer simulations, and prototypes (pilot) — to innovate the engineering construction technology; on the other hand, certain mature engineering technologies can be acquired from other countries and industries to form new engineering organizations and to transplant new engineering technologies.

The integration process has two basic steps: the experimental attempt and the cumulative consolidation. The experimental attempt refers to a variety of types of tests on innovative organizations and technologies. The feasibility and effectiveness of innovative organizations and technologies should be evaluated according to the test results. The cumulative consolidation refers to the continuous summary and refinement of technical knowledge. Through the management documents, technical standards, knowledge base, etc., the knowledge is consolidated into a knowledge system. In addition, there is an iterative process between the experimental attempt and the cumulative consolidation.

We assume that there are N subsystems in a complex project, and that the function $\tilde{f}_i$ of the ith$(i = 1,...,N)$ subsystem is determined by its design scheme, $\tilde{x}_i$. According to the aforementioned steps, we may use the following model to represent the "innovative integration" process:

$$X = \text{argmax}\ E\{E\cdots\left[E\left(\tilde{f}_1(\tilde{x}_1)\cup\tilde{f}_2(\tilde{x}_2)\cup\tilde{f}_3(\tilde{x}_3)\right]\right.$$
$$\cdots\cup\tilde{f}_N(\tilde{x}_N)\}, \tag{1}$$

where E represents the evaluation of the previous experiment, which involves the process of knowledge acquisition, and x represents the set of technical solutions, and $\cup$ represents the integrated operator.

Figure 2 illustrates the innovative integration process of a complex project. The process includes the learning process from a related organization and other industries, the technical solution-forming process through experiments, and the process of setting up a knowledge base via knowledge consolidation. Hence, innovative technologies and organizations emerge by integrating different elements.

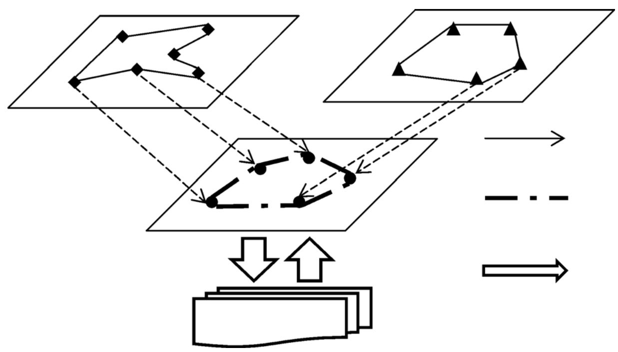

Fig. 2 Innovative integration

For the deck pavement project of the HZMB, the main complexity in the project design phase was to define the technological options for the deck pavement of the steel bridge. Being the responsible organization for the management of the project, the HZMB Authority dedicated a substantial amount of time to the innovative integration work during this phase. For the steel deck pavement program, the specific steps are listed in Table 3.

5.2.2 Functional integration

"Functional integration" refers to the process in which the relevant parties determine the technical indicators and the design of the subsystem and its interface. In addition, based on the established technical program and the technical knowledge, the relevant parties initially designate the appropriate machinery and equipment that is required to complete the engineering tasks in order to achieve the overall function of the system. At this point of the design phase, the knowledge on how to achieve the objectives of the project has been obtained, and the complex problems of the project have already been resolved. Therefore, the systematic problems need to be addressed.

Moreover, the integration process has two basic steps, namely the overall function definition and the detailed function description. On the one hand, the entire function

Table 3 Innovative integration steps of the steel bridge deck pavement

Number	Year	Innovation organization	Innovative integration activity
1	2010	The Authority entrusted the South China University of Technology to take the lead in carrying out the project of the deck pavement of the HZMB	The research group conducted extensive research on the engineering application of the deck pavement of the steel bridge, systematically compared, elected, and demonstrated certain typical pavement programs (epoxy asphalt, mastic asphalt, etc.), proposed two guiding opinions
2	Early 2012	Design unit DB01 (CCCC[a)] Highway Consultants) commissioned the South China University of Technology, which cooperated with the Hong Kong Anderson company, the Guangdong ChangDa company, Tongji University, and other professional units to conduct research work on the steel bridge pavement	A comparative study was conducted on the hot mix epoxy asphalt pavement (Japanese epoxy) and the British MA[b)]
3	At the end of 2012	The HZMB Authority required that the design units refer to the MA technology, which has more than 10 years of successful application in Hong Kong	Based on the Shenzhen-Hong Kong Western Corridor project, the professional units conducted a research on the feasibility of transplanting the British MA technology; a special coordination meeting was held in Guangzhou, where it was conclusively determined that the research direction would be oriented toward the MA technology
4	2013	The leading group of the pavement project instructed the design unit and the thematic units to conduct a concurrent research on the MA, GMA[c)] and GA[d)] technical option	Tens of thousands of test data were obtained through hundreds of indoor simulation tests and tests on stability in high outdoor temperature and low-temperature fatigue by using large-scale straight-speed loading machines introduced by Tongji University
5	At the end of 2013	Determination of the technical option	Design selection of the composite pavement structure system with a 4 cm thick SMA + 3 cm thick mastic asphalt concrete for the steel deck pavement

Note: a) China Communications Construction Company; b) Mastioc Asphalt; c) Guss Mastioc Asphalt; d) GussAsphalt

of the project can be decomposed into the function of each subsystem by employing the method of system decomposition. On the other hand, the entire function of the system would emerge by integrating the functions of the subsystems. During this step, the implementation paths, the necessary resources, and the required equipment should be carefully described.

The functional integration of complex projects can be expressed through the following model:

$$F = \mathrm{U}_{i=1}^{N} f_i(x_i, n_i, b_i, e_i), \quad (2)$$

where F is the overall function of the project and f_i is the function of each subsystem, which is determined by the technical program of the subsystem, the index requirements, the system interface, and the required equipment.

Figure 3 illustrates the functional integration process for complex projects.

In the deck pavement project of the HZMB, the functional integration of the design phase can be reflected in the definition of the device functions of the subsystems. Table 4 lists the typical cases.

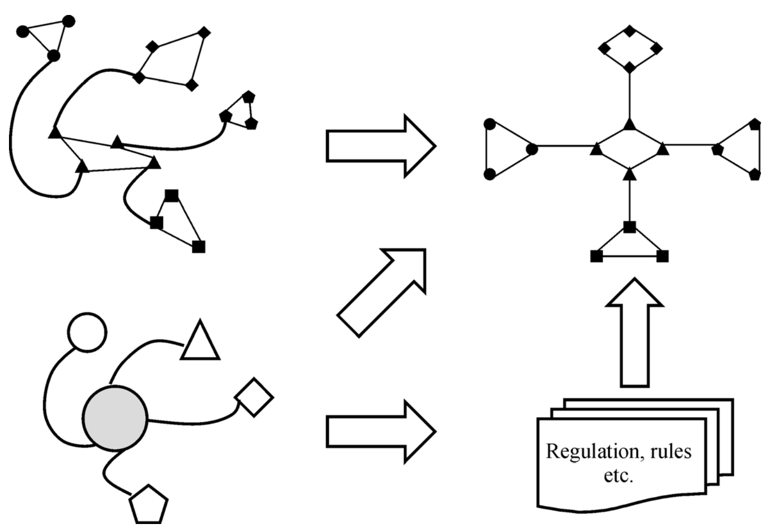

Fig. 3 Functional integration

5.3 Meta-synthesis process of the construction phase

In the construction phase, the “adaptive integration” from the “exploration” strategy was employed to set up the project organization system; then, the “efficient integration” from the “exploitation” strategy was employed to improve the actual construction performance of the project.

5.3.1 Adaptive integration

The meta-synthesis process of a complex project is an evolutionary process under the guidance of the project objectives. Hence, the entire project system develops gradually through the interaction of different types of project entities. The integrated organization of the project entities needs to meet the objectives of the project through the cooperation of the relevant entities, and to quickly respond to various uncertain events that may arise from the environment during the construction. Therefore, this process allows project entities to adapt their behaviors according to other utilities and the system environment, and through which they may form a new organization. During the process of integration, the project organization system follows the general rules, which emphasize the matching between the behaviors and the objectives. In addition, the process presents the general law that the complex system is formed through adaptive behaviors.

The primary task in the integration process of a complex project during the construction phase is to identify the integrated target object; that is, to determine which project entities should be integrated. This process is known as integrated target recognition and matching process. In the industry of infrastructure construction, there are several construction units and related departments. For a complex project, the primary task in the integration process is to determine a limited amount of project entities that have the potential to achieve the project objectives in a project-entities space with a large number of heterogeneous entities, and to connect them effectively.

After determining the integrated targets of the construction through the process of identification and matching, it is necessary to determine the real project entities in order to perform the specific construction. This process is known as the innovation of integrated construction entities. Because the entities determined in the aforementioned identification and matching process are merely the initial form of the organization, these entities cannot be directly integrated. Thus, real integrated construction entities need to be formed. These integrated construction entities can be expanded from the original initial organizations. Furthermore, in certain special cases, new integrated organizations may be established as well.

Moreover, owing to the inherent uncertainty of complex projects, duty-based and contract-based methods are not effective in certain situations. The integrated process for these problems can be guided by simple rules and structural principles (Davies et al., 2016; Eisenhardt et al., 2010). These simple rules and structural principles do not directly specify the responsibilities of the subsystems (i.e., what must be done). They are more flexible provisions, such as principles of conduct, scope of work, engineering culture, engineering spirit, and other soft rules. These rules and principles direct the subsystems toward the adaptive behaviors that need to be adopted, based on specific circumstances.

For this type of integration process, the model can be expressed as follows:

$$F = \mathrm{U}_{i=1}^{N} f_i(O_i|R), \tag{3}$$

where R represents the semi-structured rules determined by the project and O_i is the adaptive organizational behaviors of all subsystems according to R.

Figure 4 describes the adaptive integration process for a complex project. This process demonstrates the dynamic process in which various project entities in the construction process of a complex project adapt to each other and form a complex project management system through the interaction and innovative activities under the guidance of the expected project objectives.

In the construction phase of the bridge deck pavement of the HZMB, the adaptive integration consists of the following steps.

1. Attracting top companies to participate in the bid in order to guarantee the realization of the requirements that pertain to the technology and the quality. Considering that rational pricing is the source of technological innovation and that it can preserve the full enthusiasm of contractors while maintaining appropriate competition, the HZMB Authority set a rational controlling price for the deck pavement project, which included the amortized costs for various functional requirements. The method reflected the matching mechanism between the technology requirements and the supply of the capacity, and successively stimulated the participation enthusiasm of potential bidders. Based on the matching mechanism, the HZMB Authority established certain contractual terms to enhance

Table 4 Equipment function definition of the HZMB deck pavement

Number	Project name	Equipment function definition
1	Aggregate handling–production	Automated handling–production lines and equipment
2	Shot blasting and sand blasting for rust removal	Large car-type shot-blasting machine
3	Waterproofing of the deck pavement	Automatic spraying equipment

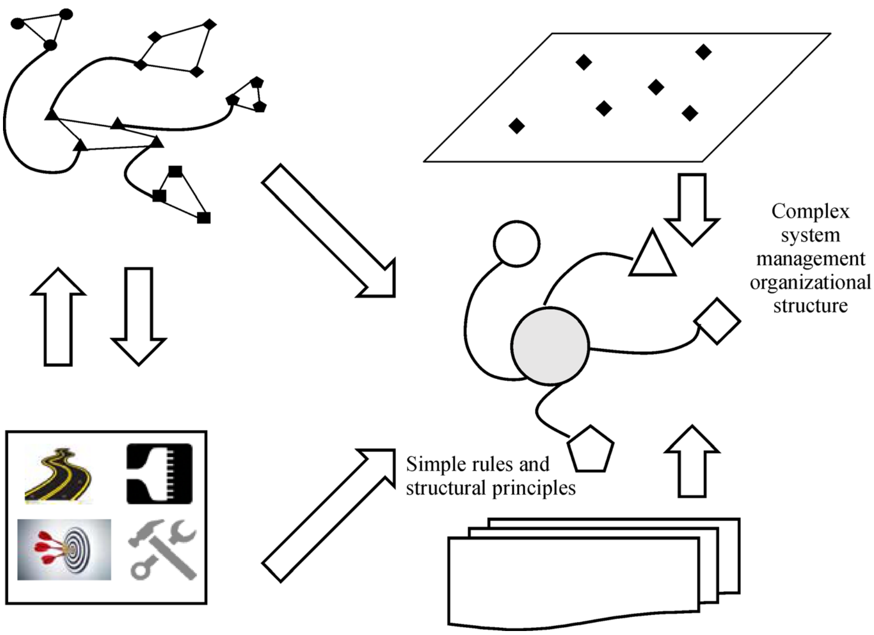

Fig. 4 Adaptive integration

the competition in the open bid. In this manner, several domestic and foreign industry leaders were attracted to participate in the bid. In addition, the total cost was reduced effectively.

2. Implementing innovative factorial construction to improve the efficiency of lean construction according to the trend of industrialization of the construction industry. It is well known that the quality of aggregate production is affected by the degree of drying of raw materials. In the deck pavement of the HZMB, to achieve the high requirements of the aggregate, the HZMB Authority decided to implement factorial construction. On the basis of this consideration, the Zhong-Shan Aggregate Plant was established, and was furnished with numerous pieces of advanced equipment, such as a coarse production line, an aggregate production line, and related automation equipment. A European-style vertical shaft alluvial crusher was used to ensure the grain size of the aggregate; a bag-type dust-extraction system and a fully enclosed transmission channel adopted from the asphalt mixing station were used to suppress the dust. To ensure the efficiency of the factorial construction, the raw materials used in the Zhong-Shan Aggregate Plant were semi-finished materials. The process of mining and crushing the raw materials took place in the stone field near the mine.

3. Establishing a risk-sharing culture, in which all entities involved in the project are partners based on the contract and jointly cope with uncertainty events. The HZMB Authority implemented the partnership with all contractors, while requiring that all contractors strictly enforce the contract to fulfill their duties in order to achieve a win-win situation on the basis of mutual understanding. In the process of bridge deck paving, owing to certain unforeseen circumstances, the completion time of the project was postponed from the original — June 2017 — to December 2017. Therefore, the relevant construction contractors had to extend their construction period, which caused a great increase in the project costs. Considering the principle of the partnership, the HZMB Authority adjusted the budget under the premise of ensuring the quality of the project; this adjustment maintained the legitimate rights and interest of the relevant construction contractors.

5.3.2 Efficient integration

"Efficient integration" refers to the optimization of the overall arrangement of the system structure and the improvement of the entire function of the project. To realize these objectives, it is necessary to establish detailed management rules, to re-engineer the organizational procedure, and to trade off several types of management elements during the construction period. Of course, all the aforementioned should be executed after the realization of the fundamental function of the engineering system.

At this point, the organization management focuses on the responsibilities of each subsystem and emphasizes the cooperation among the subsystems. The construction behavior of one subsystem is affected by its responsibility and the construction behaviors of the remaining subsystems. For the entire project, the function of the project should be optimized as a whole. Thus, the "efficient integration" can be modeled as

$$F = opt \ \mathrm{U}_{i=1}^{N} f_i\left(O_i | R, \overline{O}_i\right), \quad (4)$$

where *opt* is the optimization of the project and $\overline{O}_i$ is the construction behaviors of the remaining subsystems in the project, which are related to O_i.

Figure 5 illustrates the transition from the functional integration to the efficient integration. In the transformation process, based on the original function, the original connection relation becomes simplified and the entire structure of the system becomes distinct.

Table 5 lists the efficient integration for the aggregate plant of the HZMB.

In addition, the contractors actively fulfilled their obligations based on the contract to achieve the requirements of the HZMB Authority.

1. In response to the requirements of the HZMB Authority for the use of large-scale on-board shot-blasting machines, the contractor, namely the Zhixiang Company, conducted a wide-range research on the military industry and the ship industry at a global scale, and successfully discovered a vehicle-mounted shot-blasting machine (2-4800DH), which was manufactured by Tektronix, and was used for the blasting and rust removal of aircraft-carrier decks. The machine can replace the traditional hand-held shot-blasting machine. After the procurement of the machine, the Zhixiang Company obtained a high number of test parameters through trials, which were successfully used in the real blasting and rust removal of the HZMB steel. Through the use of the 2-4800DH car-type shot-blasting machine, the duration of the construction period was shortened by more than 30% compared with the duration of the construction period that would have resulted from the use of the traditional hand-held shot-blasting machine. In addition, the technical indicators of sand blasting met the design requirements by 100%.

2. To replace the artificial spraying with the automatic spraying equipment that was proposed by the HZMB Authority, the contractor developed fully automatic spraying equipment to lay a waterproof adhesive layer, which was in accordance with the requirements of the tender documents and contract. After conducting a high number of tests, the performance of the equipment was improved until it satisfied the project requirements of the HZMB. This equipment produced a methyl methacrylate (MMA) waterproof layer of 270000 m^2 within 100 effective working days; all quality indicators satisfied the design requirements.

In addition to the different types of integration strategies discussed previously, the meta-synthesis management framework proposed in this work has the following three

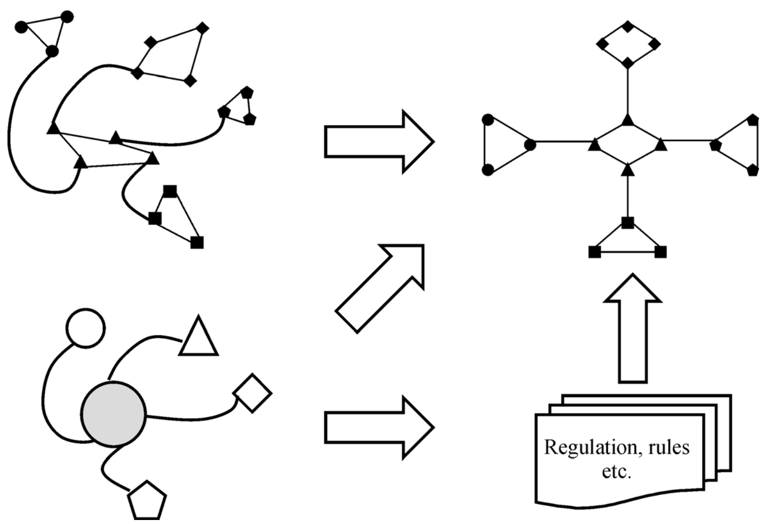

Fig. 5 Efficient integration

Table 5 Efficient integration for the aggregate plant of the HZMB

No.	Content of integration	Methods of integration
1	Factory management of the production process	Intelligent centralized control mode of the production line, mechanized operations of the entire production process, monitoring of the entire production process, entrance guard system of the processing area
2	Dust-free management of the aggregate production	Ensuring the aggregate production to be dust-free, recycling of derivative products
3	Quality control of the aggregate	Automatic weighing packaging system, memory card information control system, quality traceability

characteristics, which are presented in Fig. 6:

1. The proposed meta-synthesis management framework is a closed dynamic process. The process begins with the “innovative integration” and follows the “functional integration”–“adaptive integration”–“efficient integration” path. Each process is indispensable and contributes to the meta-synthesis individually.

2. The meta-synthesis management framework presents four evaluation dimensions of a complex project: innovation, knowledge, ability, and efficiency. These four dimensions can be used as a criterion for distinguishing the types of the integration process, as well as a means to reflect the abilities that are necessary in the meta-synthesis management.

3. The meta-synthesis management framework represents the unification of the management of a complex project. Although different strategies and methods are used in different phases, the integration goals are consistent and their organization is unified. In the deck pavement project of the HZMB, the HZMB Authority assumed the role of the center of the integration.

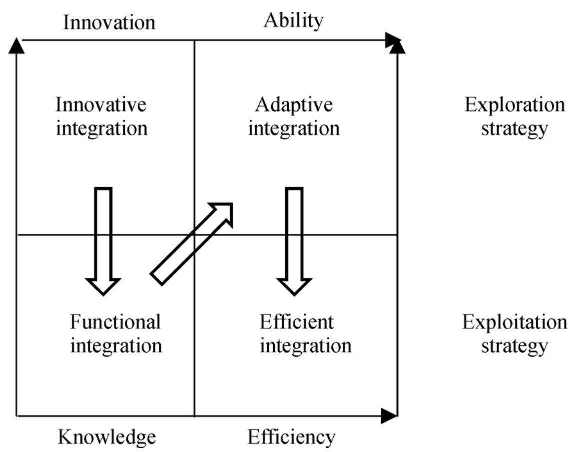

Fig. 6 Characteristics of the meta-synthesis management framework of a complex project

The meta-synthesis framework presented the following implications with regard to the practical management of a complex project:

First, the managers of a complex project should recognize that the problems that they are called to address are different from those of a general project, and that they should adopt different strategies in different project phases. The meta-synthesis framework provides a decision support tool for the managers of complex projects in order for them to adopt the most appropriate strategy.

Second, the key problems for managers are the complex problems that represent the lack necessary technologies and the uncertainty during the construction. An exploration strategy is required in order to develop innovative technologies and to set up an adaptive organization. Next, managers should consider the optimization problems that could be resolved through traditional methods, such as system engineering and project management. The meta-synthesis framework provides a decision sequence for the managers of complex projects.

Third, according to the management practice of the HZMB deck pavement project, we may observe that the HZMB Authority played a key role during all integration processes. The meta-synthesis framework emphasized on the central control of the integration regardless of the type of phase and the type of problem that needed to be addressed.

6 Conclusions

Three main contributions have been presented in this work. First, the problems of a complex project have been classified into two different categories: complex problems and systematic problems. For a complex project, the complexity was manifested in terms of the correlation between people and things, which cannot be decomposed or fragmented. Therefore, a meta-synthesis management framework proposed in the present study provides a new manner of solving complex problems by transforming them into systematic problems. Second, in this study, we proposed a new meta-synthesis management framework, which encompassed different integration strategies for different types of problems. The “exploration” strategy should be used for the transformation of complex problems into systematic problems. Next, the “exploitation” strategy should be employed to solve the systematic problems. The method proposed here has affirmed the value of system engineering and that of the PMBOK, and has offered a feasible strategy, which can be adopted for complex problems in a complex project. Third, we proposed different integration processes for each of the two types of meta-synthesis strategies for different phases of the project, which clarified the key missions and objectives of various integration strategies. The framework provides a new manner in which the two strategies can be integrated, which can be helpful in terms of guiding the management practice of complex projects. Of course, the present study has only introduced an integrated framework. The details pertaining to the integration strategies and processes, particularly the contents of the “innovative integration” and those of the “adaptive integration” in the “exploration” strategy, are not sufficient. Therefore, a further in-depth summary according to the project practice is necessary. Meanwhile, future in-depth research works on integration processes are required as well.

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