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RESEARCH ARTICLE

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Coupling and evolution mechanism of infrastructure mega-projects complex ecosystem: Case study on Hong Kong-Zhuhai-Macao Bridge

Abstract Infrastructure mega-projects (IMP), which involve complex interactions and feedback, have more significant impact on economic, social, and other systems. This paper proposes a concept—the IMP complex ecosystem—to analyze IMP from a broad perspective of organic links across engineering, social, economic, and resource environments. Moreover, this paper proposes the theoretical concept, framework, and functions for the IMP complex ecosystem based on complex ecosystem theory. First, the coupling process between IMP complex ecosystem subsystems is analyzed through material flows, energy flows, information flows, and value streams. Second, a logistic model of the IMP complex ecosystem is proposed by analyzing the evolution conditions and motivations. Third, the evolution pattern of the IMP complex ecosystem is determined. Fourth, the positive evolution strategy of the IMP complex ecosystem based on dissipative structure theory and the influencing factors of the evolutionary process is introduced. Finally, the Hong Kong-Zhuhai-Macao Bridge and *Sousa chinensis* are used as the case study. This paper also analyzes the coupling structure on the complex ecosystem of the Hong Kong-Zhuhai-Macao Bridge and investigates the coupling and evolution mechanism application of the IMP complex ecosystem on *Sousa chinensis* protection for the Hong Kong-Zhuhai-Macao Bridge project.

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1 Introduction

Infrastructure mega-projects (IMP) are characterized by huge large-scale investments, multiple participants, long lifecycle, heterogeneous elements, self-adaptability characteristics, and complexity. Specifically, IMP have a more significant external impact on the economy, society, and environment compared with common projects. The research on the management of IMP should therefore be investigated with a broad scope by studying the coupling and evolution mechanism between IMP and society, economy, resources, and environment rather than limiting IMP to its engineering system only. This novel research paradigm can play an important role in improving our analysis on the multifaceted relationship of subsystems of the complex ecosystem; reveal the inherent coupling relationship and evolution of the system; and promote collaborative symbiosis between IMP subsystems.

IMP management research commenced in the late 1980s to the early 1990s. In 1995, engineering management research focused on issues on IMP management. These researches mainly focused on project collaboration, lifecycle cost, decision-making and information technologies. In 2005, the research scope of IMP management extended from project management (such as risk, schedule, and cost) to decision-making and planning phases. Scholars also preferred to view IMP management from a global perspective (Levitt, 2007).

Managers should consider IMP complexities in the context of increasing societal impact (Castejon-Limas et al., 2011). Subsequently, novel system engineering and system methods were applied to investigate IMP management (Calvano and John, 2004). According to Ottino (2004), managers should acquire the ability to analyze and cope with such complexities, and this objective may be achieved by investigating several complex phenomena that are not relevant to IMP. Guo (2007) proposed that scholars should integrate practice and management science from the perspective of social responsibility to solve complex project problems. Sheng and You (2007) applied system integration methods to analyze IMP systems to cope with complexities. Sauser and Boardman (2008) proposed a management concept for the system of systems (SoS) of an engineering project. The main features of SoS generally include self-organization, belongingness, connectivity, variety, and emergence.

Zhang and Xue (1995) assumed that many complex engineering projects have caused wide and deep impacts on the society, economy, and environment. Thus, management should consider "engineering integrity" rather than simply viewing projects from the engineering aspect only. Sahely et al. (2005) proposed that infrastructures should be studied from a wide perspective. A theoretical framework focusing on material energy and information, and the relationship between infrastructure and the economy, society, and environment, should be considered.

The theory of social-economic-natural complex ecosystem provides an ideal paradigm in ensuring "engineering integrity" in IMP management. Ma and Wang (1984) proposed the theory of social-economic-natural complex ecosystem based on the concept of ecosystems (Tansley, 1935) and eco-economic complex systems (Odum, 1983), which provide a theoretical framework for effectively analyzing the above problems. On the basis of traditional ecology theory, the framework emphasizes the relationship between humans and the environment by focusing on economic, social, and resource environment system interaction. In addition, the framework considers the major fundamental issues of the modern society as a whole (i.e., composite system) based on the assumption that issues are directly or indirectly influenced by the social system, natural environment, and economy. A complex system is formed by the synergistic action between the social-economic system of humans and the ecosystem. Subsequently, Wang and Ouyang (2012) extended the complex ecosystem in 1987 by employing the theory on the ecological planning and construction of Dafeng county, Hainan province, Yangzhou city, and Jiangsu province.

In recent years, many scholars have applied the complex ecosystem theory to different fields, and many research initiatives have been conducted on several related issues, including the definition, characteristics, coupling, management, and application of complex ecosystems. Yuan and Han (1998) believed that "the complex ecosystem" is not a set of subsystems, but multiple independent subsystems with certain patterns of interactions. Even the phrasing "natural-social-economic" suggests a complex ecosystem. Hao and Qin (2003) proposed that the complex ecosystem is composed of human-oriented socio-economic system and natural ecosystem with synergies in specific space. Qin (2008) analyzed the self-organized characteristics of complex ecosystems, including their dynamics, nonlinear self-feedback, cyclic regeneration, and collaborative symbiosis. Several scholars introduced the complex ecosystem theory to different fields, such as in cities, mining areas, and transportation, and analyzed their system structure and coupling relationship. Shen and Yang (2007) analyzed the application of complex ecosystems on the transportation system and reported that the complex ecosystem is an open, complex, and large-scale dynamic system with unified structures and functions, in which subsystems interact and interpenetrate. Wang and Li (2014) investigated the coupling mechanism of a coal mining complex ecosystem. Several scholars also extended the management issues of complex ecosystems, such as ecosystem management methods and regulatory mechanisms (Christian et al., 1996; Tian et al., 2006), ecosystem restoration, and environmental governance (Bossel, 2001; Fan et al., 2003). In summary, the complex ecosystem theory has been extended to various perspectives, including urban and regional environmental protection and ecological planning, planning and design of traffic roads, and other specific system areas. However, the complex ecosystem theory is not used in IMP. Most studies on IMP management have failed to analyze the characteristics and patterns of material and energy flows between and within the internal and external systems of IMP.

Considering the above research gaps, this paper systematically studies the structure and function of the IMP complex ecosystem and the coupling mechanism between the subsystems of economy, society, and resource environments. Specifically, this paper analyzes the process and exchange mechanism of material, energy, information, and value flows across the four main subsystems (i.e., engineering, economy, society, and resource environment systems) in the IMP complex ecosystem, as the above mechanism plays a central role in IMP ecosystem development.

2 Framework and function of IMP complex ecosystem

2.1 Definition

The construction and operation of IMP is the process and outcome of human social and economic activities. The construction activities of IMP frequently affect the development process of the economy and society, and they alter the original characteristics of the geological environment. The construction and operation of IMP are related to public interest during the construction period and to the distribution and balance of interests across different generations. Therefore, the construction activities of IMP have huge impacts on the sustainable development of the society and economy of a region and the entire society. Furthermore, IMP represent the comprehensive capability of a nation combined with historical and cultural values and social and economic significance.

To reduce the conflicts between humans and the environment, the social and economic activities in subsystem construction and operation of IMP complex ecosystem should be considered. These subsystems are mutually constrained and interdependent, and they are beneficial for integrating nature with social economy and achieving rational resource allocation in IMP complex ecosystem. This characterization indicates that IMP is a system and a component of other large systems, and the role and value of IMP must be completely reflected in a broad context.

Inspired by social-economic-natural complex system theory, this paper defines an IMP complex ecosystem as an artificial complex system with huge impacts on the society, economy, and nature. An IMP complex ecosystem is also an engineering-social-economic-natural system that are led by engineering construction and operation behavior, and aimed for economic development and streaming by the social subsystem, and supported by resource environment subsystems. The main functions of IMP complex ecosystem are based on the interactions and feedback of material cycles, energy flows, and the natural environment. The radiation scope includes enterprises and individuals directly involved in construction and operation, and cities and regions that are indirectly affected by IMP complex ecosystem.

2.2 Composition and function of IMP complex ecosystem

Any ecosystem is divided into biological and non-biological environment systems. Thus, this paper considers the IMP complex ecosystem in terms of the relationship between humans and the natural environment (Fig. 1).

Social and economic subsystems are formed by the relationships and activities among IMP stakeholders. Therefore, the IMP complex ecosystem consists of engineering, social, economic, and resource environment subsystems. We construct the IMP complex ecosystem based on the theory of urban and regional complex ecosystems proposed by Wang and Ouyang (2012), as shown in Fig. 2.

The major IMP stakeholders include design, construction, and operating units and the public (i.e., DU, CU, OU, and P in Fig. 2), which are composed of social subsystems. The subsystems provide management, regulation, human, and intellectual support during the construction and operation of IMP. Meanwhile, the economic subsystem includes production, distribution, exchange, use, and consumption that accompany IMP construction and operation.

The resource environment subsystem includes environmental and resource elements, which are fundamental in maintaining the material basis and space conditions for the construction and operation of IMP. Environmental elements refer to all the natural factors, including spatial area, geological topography, climate, hydrology, and soil, that directly or indirectly affect IMP construction and operation. Resource elements refer to the factors, such as climate, water, land, biological, mineral, and energy resources, in the construction and operation of IMP. Resource and environment subsystems provide the material and energy base for the economic subsystems of IMP, and these subsystems support the social subsystem but constrain the construction and operation of IMP.

Subsystems are interdependent through the material cycles, energy flows, information transfer, and value transformation within and between subsystems. The structures, functions, and development laws on the subsystems of IMP complex ecosystem vary, and their existence and development are constrained by other subsystem structures and functions. The subsystem functions of IMP complex ecosystem are shown in Table 1.

The major infrastructure of an engineering subsystem

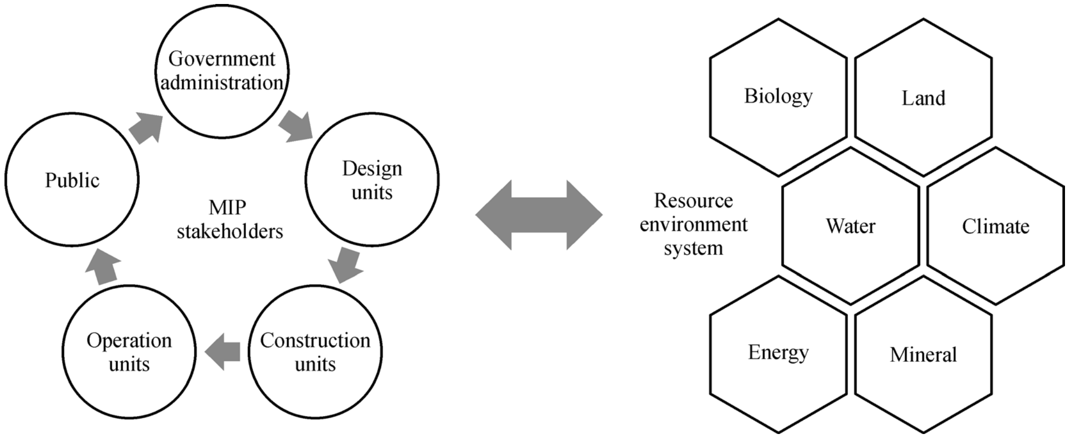

Fig. 1 Basic relationship of IMP complex ecosystems

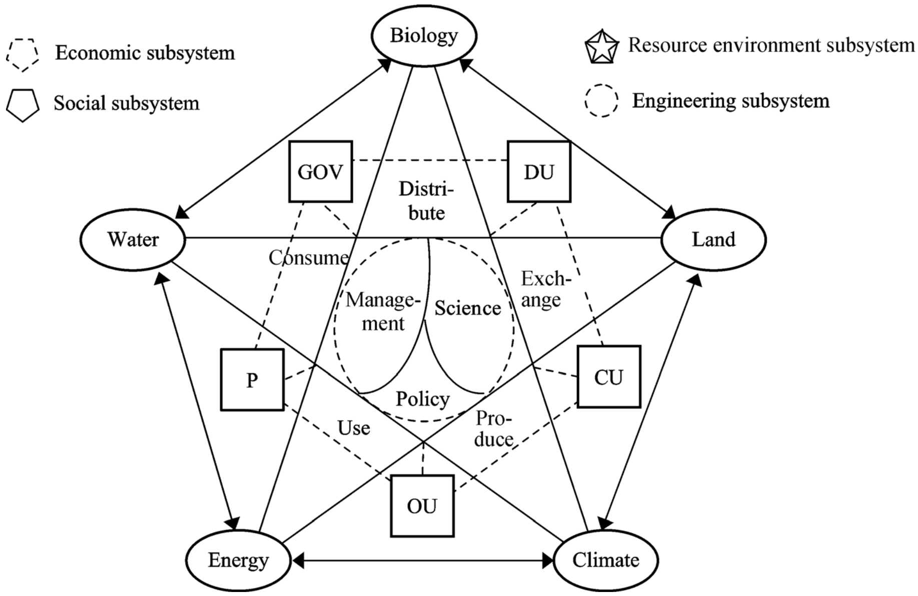

Fig. 2 Structure of IMP complex ecosystem

Table 1 Subsystem composition and function of IMP complex ecosystem

Subsystem	Basic description	Function
Engineering subsystem	Infrastructure artificial systems for IMP.	Main body of IMP complex system; main outputs of activities in the social, economic, and resource environments.
Economic subsystem	Stakeholders conduct economic activities in the construction and operation of IMP, which include the production, distribution, exchange, and consumption. This condition forms a new system in which the value, energy, and information exchange are transformed and conveyed in different entities.	Construction and operation are the main processes to form the IMP ecosystem.
Social subsystem	Social subsystem mainly considers the stakeholders, such as engineering administration, construction enterprises, and public and maintains the economic activities in the construction and operation.	Social subsystem provides management, control, human resource, and intelligence for the IMP complex ecosystem.
Resource environment subsystem	The system provides atmosphere, water, soil, biology, minerals, and energy in the construction and operation of IMP.	The system provides materials and energy in the construction and operation of IMP, which are regarded the limitations and foundations of the IMP complex ecosystem.

refers to the main body of the IMP complex ecosystem. Meanwhile, the social subsystem ensures the effective operation and development of an economic subsystem. The core function of the social subsystem is to maintain the coordination and balance of IMP complex ecosystem. The economic subsystem plays a dominant role in the IMP system, and the economic situation and structure directly affect the scale of IMP. Moreover, economic activities are the main factors that promote the construction and operation of IMP and the impacts on resources and the environment. Thus, the resource environment subsystem plays a fundamental role in the design, existence, and development of IMP complex ecosystem. The resource environment subsystem also provides the resources to develop the social and economic subsystem and determines the scale and features of IMP complex ecosystem.

3 Coupling mechanism of IMP complex ecosystem

3.1 Coupling modes of IMP complex ecosystem

The IMP complex ecosystem refers to the interaction process and coupling relationship between the subsystems of IMP complex ecosystem through material flows, energy flows, information flows, and value streams. The coupling process between the subsystems is conveyed by material cycles, energy flows, information transfer, and value transformation.

Considering the intricacies of a complex ecosystem, the general theory and methodology of conventional ecosystems cannot be directly applied to the current study. The coupling relationship of IMP systems should thus be investigated given the two-way energy flow and material recycling of complex ecosystems. In this manner, energy consumption may be reduced, flow efficiency is improved, the balance of positive and negative feedback is ensured, and positive evolution is promoted.

The coupling of an IMP complex ecosystem is divided into two types, namely, between subsystems and within subsystems. The coupling between subsystems in an IMP complex ecosystem ensures energy and material flows, which in turn maintain the operation and information exchange between these subsystems. The essential elements of IMP complex ecosystem follow ecological and economic laws that support the exchange, circulation, and transformation of materials, energy, and information. Therefore, the engineering subsystem is inseparable, interrelated, and interacts with the economic, social, and resource environment subsystems.

Compared with common ecosystems that constantly rely on natural resource subsystems, the engineering subsystem is regarded the main body of IMP complex ecosystem. In the IMP complex ecosystem, the functions of natural resource, economic, and social subsystems are to provide the basic material and energy flows, value flows, and information flows, respectively. The entire coupling system aims for sustainable construction and operation. The information flows of social subsystems are mainly conducted through human decision-making, behavioral, and management system arrangements. These flows convey the materials of engineering, economic, and natural resource subsystems and produce waste in the resource environment subsystem. The production, distribution, exchange, consumption, and reproduction activities in the economic subsystem impact the construction of the engineering subsystem. Such impacts include the provision of engineering materials, artifacts, and artificial energy to the engineering subsystem; discharge of wastes into the environmental subsystem; and conformance with the management and regulations of the social subsystem. Resource circulation and energy flows in the economic subsystem include the provision of engineering raw materials, allocation of primary energy, and decomposition and consumption of wastes in all phases of the lifecycle.

The construction and sustainable development goals of IMP complex ecosystems are achieved through the coupling between subsystems and the integration of structures and functions of different subsystems. The coupling mechanism between the subsystems of an IMP complex ecosystem is shown in Fig. 3.

The coupling within subsystems of an IMP complex ecosystem is represented by the movement of various flows within the subsystem. The social subsystem is composed of science and technology, policy, and management elements, which are handled though information flows. The economic subsystem is composed of coupling relations among economic entities, including the design, construction, or operation of enterprises, the public, and other economic sections, as evidenced by their corresponding value streams. The resource environment subsystem is coupled with elements, such as atmosphere, water, soil, biology, minerals and energy, which are handled through material and energy flows. The coupling modes within the subsystems of IMP complex ecosystem are shown in Fig. 4.

3.2 Analysis on coupling flow in IMP complex ecosystem

The coupling relationship between the subsystems of an IMP complex ecosystem is obtained through material

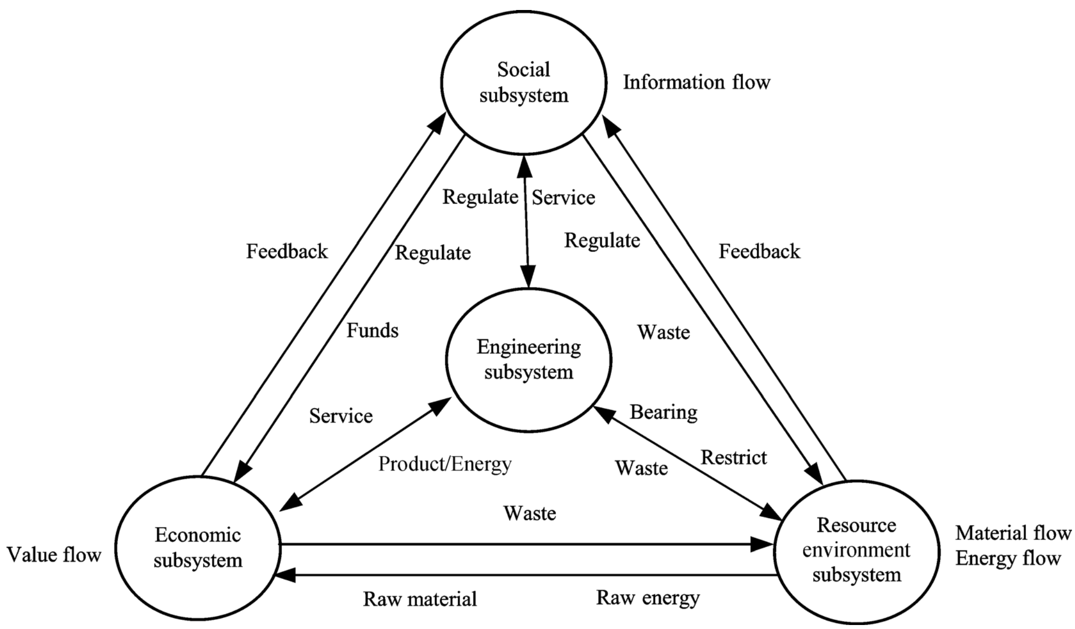

Fig. 3 Coupling relationship between the subsystems of IMP complex ecosystem

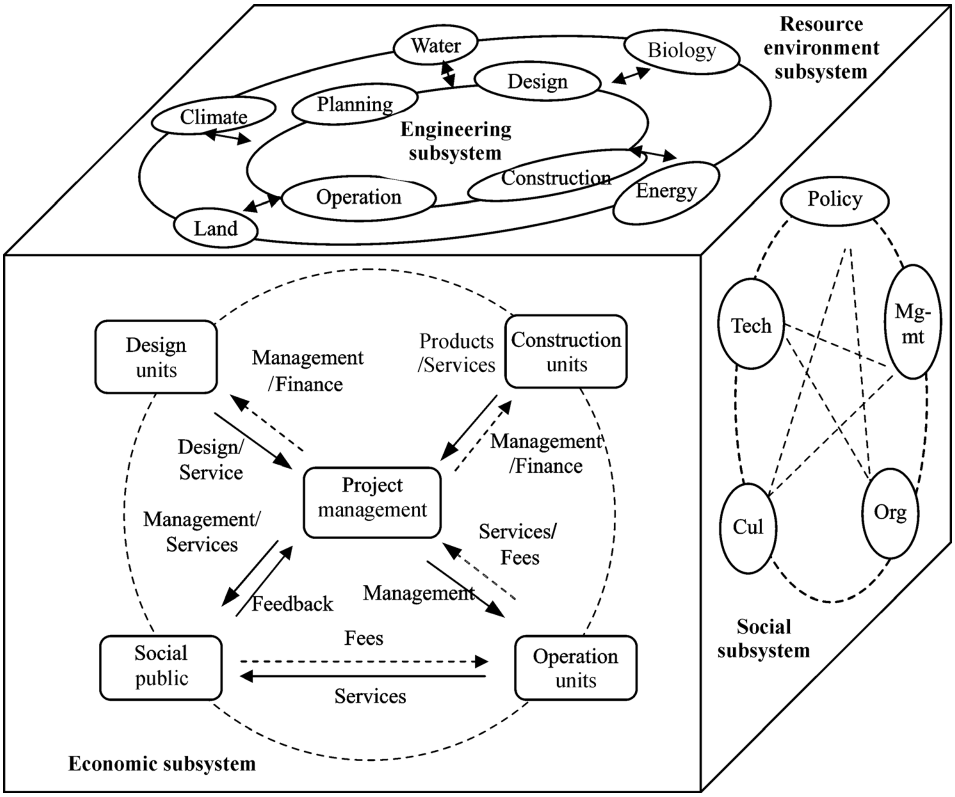

Fig. 4 Coupling modes within subsystems of IMP complex ecosystem

cycles, energy flow, information transmission, and value transformation.

3.2.1 Material cycles

The material cycles of IMP complex ecosystem refer to the consumption of resources and substances, the discharge of wastes to nature, and the provision of services to engineering users.

Material cycles include natural material flows, artificial product streams, and waste streams. Natural material flows are ecological flows driven by nature, including air and water flows. High quantity and instability are the main characteristics of natural material flows, and their strength and speed directly affect the construction and operation of IMP. Artificial product flows are a set of materials involved in IMP construction and functions. Waste flows include waste water, waste gas, and waste residues. The speed and size of material cycles depend on the needs and behavior of IMP stakeholders.

3.2.2 Energy flow

Energy flows refer to the process of energy transfer, circulation, and dissipation within and across systems. Energy flows should satisfy the requirements of IMP construction and operation, which involve raw energy in natural ecosystems and artificial energy. Raw energy includes solar energy, water, wind, oil and ore, whereas artificial energy includes electricity, gasoline, diesel, and liquefied petroleum gas.

The efficiency of energy flows is closely related to the structure of energy, production, and consumption of IMP. The energy flow is oriented by value streams, passed through material flows, and adjusted by information flows.

3.2.3 Information transmission

The information flows of IMP complex ecosystem refer to the transmission and integration of information of construction, design, and operating units and the public. Material flows in the ecosystem can be observed in real time, and they are regarded as accurate and valuable information flows. The utilization of information resources is an important measure in determining the efficiency and coordination of IMP complex ecosystem.

Information is derived from the production and living function of a complex ecosystem. The ecosystem is improved sustainably and stably with closely connected components through information feedback (Wang et al., 1989).

Extensive information exchange can be observed between and within the subsystems of IMP complex ecosystem. Considerable information influences major engineering design, construction, operation and maintenance, technology, management, market, public, and owners. Information promotes integrative capabilities (i.e., resource management, technology configuration, energy management, material flow management, and recycling efficiency) of engineering, social, and resource environment subsystems through the collection, collation, storage, accumulation, and feedback of information.

3.2.4 Value transformation

The value transformation of an IMP complex ecosystem refers to the process of transforming engineering and other materials and energy into physical entities.

Value stream is evident in the entire lifecycle of IMP complex ecosystem. In the construction phase, enterprises search for partners in the design, construction, and purchase of materials and acquisition of labor, which in turn result in the transformation of funds into operational construction materials and labor. Construction enterprises also transform the value of materials and labor into engineering entities. In the operation phase, users possess the right to implement projects and deliver services with corresponding payment, while operating enterprises use funds to manage projects in terms of maintenance and operation. Engineering and other subsystems also interact with each other through money flows during construction and operation. For example, the special requirements of materials, technologies, or equipment for IMP have altered the required technologies or capabilities of different enterprises, which in turn have resulted in their corresponding changes in economic value.

The coupling flows between the subsystems of different stages of IMP are shown in Table 2.

4 Evolutionary mechanism of IMP complex ecosystem

4.1 Evolutionary conditions and motivations

IMP complex ecosystem are self-organized and hetero-organized because of the combined characteristics of general and complex systems.

The structure of IMP complex ecosystem is dissipative, and its self-organizing feature allows the complex ecosystem to achieve higher-level self-organization, i.e., exponential growth is achieved by the social, economic, and resource environments, as evidenced by their in-between subsystems and their respective internal nonlinear roles. However, the IMP complex ecosystem is constrained by resource inputs and environmental capacity from the resource environment subsystem. Nonetheless, the IMP complex ecosystem can achieve evolution and balance with the combination of the driving factors and constraints.

Meanwhile, as a complex artificial system, the hetero-organizational characteristics of IMP complex ecosystem result in the mutation of system evolution and may break the balance of self-organization evolution. This condition is regarded a re-evolution process from order to disorder, then back to order.

4.2 Evolution process

The evolution process of an IMP complex ecosystem follows the ecological logistic development mechanism. Logistic development involves the complex integration of positive feedback growth and negative feedback equilibrium (Zhang and Hu, 1995), which is characterized by the classic ecological logistic model. The model is widely applied in the field of population ecology to describe the effect of the dynamic time-space relationship on biological population. On the basis of population ecology theory, logistic growth is developed as a simple form of population growth model in restricted environments. Similar to the evolution of biological populations, the space condition of an IMP complex ecosystem is limited by the resource environment subsystem. The development of IMP complex ecosystem is also subject to the design and function of the engineering subsystem and thus cannot grow indefinitely. Therefore, the evolution of the IMP complex ecosystem is a logistic development mechanism. The logistic model is defined as follows:

$$\frac{\mathrm{d}N(t)}{\mathrm{d}t} = r(t)N(t)\left(\frac{K(t)-N(t)}{K(t)}\right), \tag{1}$$

Table 2 Analysis of coupling flows between the subsystems of different IMP stages

Stage	The main subject	The subsystem	Main coupling flow
Preliminary planning stage	Government administration, experts, and the public	Social subsystem	Information transmission
Design stage	Government administration, design units, experts, and the public	Social, economic, and resource environmental subsystems	Information transmission
Construction stage	Government administration, construction units, experts, and the public	Engineering, social, economic, and resource environmental subsystems	Material cycles, value transformation, energy flow, and information transmission
Operation stage	Government administration, operation units, experts, and the public	Engineering, social, economic, and resource environmental subsystems	Value transformation, material cycles, energy flow, and information transmission

where $N(t)$ is the comprehensive indicator of the development of an IMP complex ecosystem and determined by the comprehensive development levels of social, economic, engineering, and resource environment subsystems. The levels include management capacity, policy system, culture and education, and science and technology development in the social subsystem; production efficiency, market exchange and distribution, resource and product utilization, waste decomposition, and processing capacity in the economic subsystem; completion degree, structure, and function maturity in the engineering subsystem; carrying capacity, renewable resources and non-renewable resources, biological population size, and succession in the resource environment subsystem. Accordingly,

$\frac{\mathrm{d}N(t)}{\mathrm{d}t}$ is the instantaneous development rate of the IMP complex ecosystem;

$r(t)$ is the maximum development rate of $N(t)$, which denotes the maximum development rate without external restrictions under certain circumstances;

$K(t)$ is the highest development level of the IMP complex ecosystem in terms of social, economic, and technological development levels, resource inputs, and environment circumstances; and

$\frac{K(t)-N(t)}{K(t)}$ is the logistic coefficient, which denotes the braking effect on the development of the IMP complex ecosystem. The coefficient approaches 0 as N approaches the highest degree K, which indicates that development rate gradually decelerates and reaches the highest level.

The evolution process of the logistic development mechanism of IMP complex ecosystem is shown in Fig. 5.

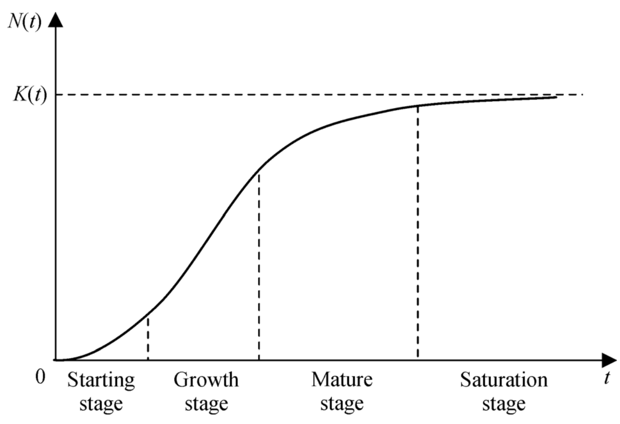

Fig. 5 Simple form of evolutionary process of IMP complex ecosystem

However, the construction of IMP itself possesses artificial construction behavior and controls, which include pre-demonstration, decision making, organization, onsite management, and regulation of construction and operation of IMP due to the organizational characteristics of an artificial complex system. Nonetheless, this condition can lead to strong linkages and mutual promotion of economic and social systems by creating new structures and functions to overcome the growth limitation of the original self-organization, thereby promoting higher-level evolution through IMP operation and control.

The influencing coefficient of the artificial regulation mechanism, such as social and economic activities, is set as λ. The logistic model can therefore be improved as follows:

$$\frac{\mathrm{d}N(t_i)}{\mathrm{d}t_i}=r(t_i)N(t_i)\left(\frac{K(t_i)(1+\lambda)-N(t_i)}{K(t_i)}\right), \quad (2)$$

where $N(t_i)$, $\frac{\mathrm{d}N(t_i)}{\mathrm{d}t_i}$, $r(t_i)$, and $K(t_i)$ represent the development degree of the system, instantaneous rate of development, the maximum development rate, and the maximum degree of development at different stages of i in the development of the IMP complex ecosystem.

Equation (2) can be solved by

$$N(t_i)=\frac{K(t_i)(1+\lambda)}{1+c\mathrm{e}^{-r(t_i)}}. \quad (3)$$

The value of λ may be positive or negative depending on the rationality and validity of the artificial control mechanism. Furthermore, λ is a compound logistic curve with combined multiple curves. System evolution and development generally correspond to complex behavior and trajectory.

Given the different stage development of the IMP lifecycle, the collaborative symbiosis of subsystems of the IMP is regarded advanced under the premise of reasonable government intervention. Figure 6 shows the ladder-like rise in the trend and economic efficiency improvement of the construction and operation units.

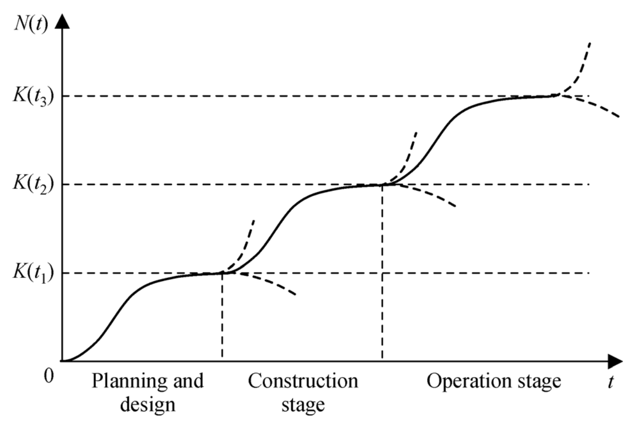

Fig. 6 Evolution process of IMP complex ecosystem

In the early phase of planning and design, the construction and operation of IMP have not yet commenced. This stage is a process of self-organization evolution. However, preliminary stage demonstration and design rationality can affect the evolution direction of the entire complex ecosystem in subsequent stages.

In the construction phase, the construction activities based on the engineering demonstration and design directly affect the balance of the original complex ecosystem. The entire system may show positive evolution or reverse evolution in varying degrees. The evolution is influenced by the complete and reasonable degree difference of the early planning and design, as shown in Fig. 6.

The construction process of the IMP involves synergies in social, economic, and resource environment subsystem processes. Human factors play a positive role in this process. The management and regulation of decision making, organization, and onsite activities directly affect the evolution of complex ecosystem, as evidenced by the dominant evolutionary characteristics of the organization. The structure of the entire ecosystem and the interaction between subsystems usually alter after project completion, which suggest that evolution processes occur in subsequent phases under reasonable and effective artificial control.

Two additional factors can affect the evolution process of IMP complex ecosystem. The first factor involves the gap between structural-functional engineering and design goal, whereas the second factor involves the interaction between the engineering subsystem with other subsystems. For example, if the construction process does not solve the problem of waste disposal that usually occurs in the social, economic, and engineering subsystems, then construction directly affects and destroys the structure, function, ecology, and environment of the original resource environment subsystem, which then lead to the reverse evolution of the entire complex ecosystem.

In the operational phase, the IMP complex ecosystem typically affects the surroundings and broader areas. The inputs and outputs of material flows, energy flows, value streams, and information flows in relation to the external system moves the entire complex ecosystem to the next evolution stage, which may be in the form of either positive or reverse evolution.

4.3 Evolutionary influencing factors and evolutionary strategies

4.3.1 Influencing factors

In formula (3), the evolution of the IMP complex ecosystem is determined by $r(t_i)$ and $K(t_i)$, in which $r(t_i)$ determines the speed of system development and $K(t_i)$ determines the highest development degree of the system.

Variable $r(t_i)$ is influenced by material, energy, value input, output speed, and efficiency factors in different IMP stages and reflected as the cooperative relationship and operating efficiency between different subsystems. Variable $K(t_i)$ is influenced and constrained by social, economic, and technological development levels, capital, human and resource inputs, and environmental conditions. Negative feedback is also considered, as it can lead to the reverse evolution of the entire complex ecosystem, including the external resources (e.g., geological topography, climatic factors, hydrology, biological ecology, the environment, design and construction quality, safety accidents, social resource integration, technical research, and ecological pollution). To maintain the upward trend for formula (3), a reasonable evolutionary strategy should be adopted.

4.3.2 Evolutionary strategies

One of the purposes of IMP is to accelerate social progress and economic development. Additionally, IMP construction inevitably alters the natural environment. If proper environmental protection planning and governance measures are lacking, or if the carrying capacity of the environmental resource subsystem is beyond the expected, then the reverse evolution of IMP complex ecosystem may occur.

According to dissipative structure theory, an isolated system is a process of entropy increase, and the system continuously moves from order to disorder. If the system is a dissipative structure and negative entropy is introduced, then the system can attain an orderly state in which economic, social, and environmental developments are altogether coordinated. Therefore, openness is an important factor of an orderly system. However, an open system is often unnecessary in ensuring an orderly system given that positive entropy flows from a dissipative structure system to accelerate the disorder process (Shen et al., 1987). Therefore, introducing negative entropy from the external system is necessary to reduce system entropy values.

The negative entropy of a complex ecosystem refers to the input and control process of materials, energy, information, and culture. The negative entropy of the input can be in the form of external funds, emerging industries, advanced management methods, and advanced cultural concepts. The control process of negative system entropy aims to control and coordinate environment, economy, and social development relationships. However, the negative entropy process of the resource environment subsystem is a passive process. By contrast, the social and economic subsystems are artificially controlled systems, and their negative entropy process is an active process.

Humans play a central role in the co-evolution of complex ecosystems (Wang and Ouyang, 2012). Their participation in IMP directly and indirectly affects the engineering subsystem through their respective social and economic activities, which in turn influences resource environment subsystems. The Project Management Department in particular can significantly impact subsystems, as it is the organizer and regulator of the complex ecosystem. By means of the management system, policy, and organizational culture, the department controls and changes the direction and speed of material, energy, information, and value flows of subsystems to stimulate a positive feedback effect and reduce a negative feedback effect, thereby promoting the positive system evolution. Therefore, maintaining openness is imperative to ensure the introduction of negative entropy, achieve the coordinated development of the IMP complex ecosystem, and overcome entropy increase. The entropy reduction and positive evolution of the entire complex ecosystem can be achieved by adopting human control methods to manage in-between subsystem and internal subsystem relations.

The benign circulation of an IMP complex ecosystem is divided into self-organization and artificial control mechanisms, and the main IMP functions are automatically adjusted depending on dissipative structure and self-organization characteristics. Meanwhile, IMP construction and operation are conducted through societal and economic activities, in which organizational characteristics and artificial control mechanisms are apparent.

The system reconfiguration of internal resources and energy can be directly or indirectly achieved through the artificial control structure and function of the system and appropriate signal and guidance values. This process can help attain the objectives of IMP construction and operation and promote positive evolution of the composite ecosystem. Specific measurements for artificial control include the following: introduction of external negative entropy factors; introduction of external funds and talents; use of modern technology; adaptation of advanced management methods and cultural concepts; and reasonable control and coordination of natural, economic, and social development relations.

5 Case analysis of Hong Kong-Zhuhai-Macao Bridge

The Hong Kong-Zhuhai-Macao Bridge, an IMP that connects Guangdong, Hong Kong, and Macao, is regarded a complex ecosystem. The engineering subsystem of this bridge is mainly composed of Hong Kong, Zhuhai, and Macao project entities. The social subsystem is represented by the Hong Kong-Zhuhai-Macao Bridge Authority. The economic subsystem is mainly composed of engineering construction, which is performed by the operation unit. The resource environment subsystem consists of Guangdong, Hong Kong, and Macao climate conditions and the Lingding Sea and marine resources.

The construction of the Hong Kong-Zhuhai-Macao Bridge is regarded a coupling process between the social and economic subsystems, and the initiative entails material and energy factors and waste emission for the resource environment subsystem. The construction implies entropy reduction for the social and economic subsystems, and the process allows these subsystems to reach higher-levels of orderly evolution. However, entropy may increase (i.e., leading to disorder) and inverse evolution may occur in the resource environment subsystem.

To promote the positive evolution of the resource environment subsystem and to ensure the healthy development of the complex ecosystem, a critical challenge for the management of the Hong Kong-Zhuhai-Macao Bridge construction is to reduce entropy increase while facilitating a comprisable degree of entropy reduction. The Hong Kong-Zhuhai-Macao Bridge crosses the main waters of Lingding Sea, which is an important area for fish breeding and fattening in the northern coast of South China Sea.

The population of *Sousa chinensis* in the Pearl River estuary is reportedly the largest population in the world, and protection initiatives is extremely important for species conservation, especially in China. *Sousa chinensis* is an essential part of the resource environment system. Several social and economic activities are involved in the construction aspect of the engineering system, and these influences have altered the distribution of *Sousa chinensis* population considerably. Aiming to reduce the negative impacts, the authorities and stakeholders considered many approaches for engineering and economic subsystems of the Hong Kong-Zhuhai-Macao Bridge. The protection of *Sousa chinensis* is an important issue during bridge construction. The entire construction even generated considerable continuous coupling energy flows across engineering, economy, society, and resource environment subsystems. In this paper, the Hong Kong-Zhuhai-Macao Bridge is therefore used as the representative case to analyze IMP complex ecosystem.

We analyze the entropy increase of biological resources of *Sousa chinensis* and the management activities of entropy reduction implemented by the Hong Kong-Zhuhai-Macao Bridge Authority by considering the protection of *Sousa chinensis* in the resource environment subsystem.

The main project (Hong Kong-Zhuhai-Macao Bridge) crosses the national conservation area of *Sousa chinensis* in the Pearl River estuary of Guangdong. Two artificial islands and part of the bridge are located in the national conservation area. The construction of the bridge inevitably and adversely affects *Sousa chinensis* populations and produce considerable entropy activities, such as construction noise interference, loss or fragmentation of important habitats.

On the basis of IMP complex ecosystem theory, the above activities are closely intertwined with processes of entropy increase, particularly, from engineering, social, and economic subsystems to the resource environment subsystem (Fig. 7).

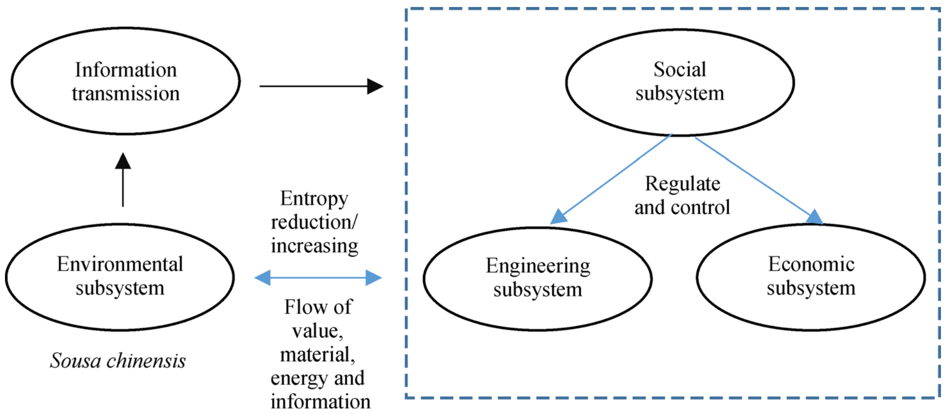

Fig. 7 Coupling relationship analysis of the complex ecosystem of Hong Kong-Zhuhai-Macao Bridge

On the basis of the coupling and evolution mechanisms of IMP complex ecosystem, the key factor for improving the negative impact on the construction of the Hong Kong-Zhuhai-Macao Bridge is to maintain the openness of the complex system. The social subsystem, which is directed by the Hong Kong-Zhuhai-Macao Bridge Authority, need use sufficient information flows for conducting management activities. To achieve the entropy reduction and positive evolution on the complex ecosystem of Hong Kong-Zhuhai-Macao Bridge, the negative entropy factors should be introduced and artificial control should be adopted for factor integration.

The first priority of the Hong Kong-Zhuhai-Macao Bridge Authority is information flows for *Sousa chinensis* protection. At the feasibility demonstration stage, an investigation on Sousa chinensis and fishery resources and an evaluation of bridge construction impact on *Sousa chinensis* and fishery resources at different construction phases should be conducted by the Hong Kong-Zhuhai-Macao Bridge Authority. A feasibility demonstration can provide scientific evidence on the ecological protection of fisheries and protected areas at different construction sections of the bridge. The demonstration can also supplement the basic information on environmental protection acceptance after project completion.

The survey on *Sousa chinensis* conducted for the Hong Kong-Zhuhai-Macao Bridge IMP from 2005 to 2016 are shown in Table 3.

Information flow based on investigation should be analyzed in terms of the positive evolution strategy of IMP complex ecosystem. The process of entropy increase should also be considered. The following points can be achieved by maintaining openness of the Hong Kong-Zhuhai-Macao Bridge system and by introducing the negative entropy factor to ensure continuous enhancement of information flows.

(1) Reduce entropy increase from social and economic subsystems to resource environment subsystem, including the following: Make an integrated planning for the construction scheme and design in the stage of project design, apply large-scaled, industrialized, standardized, and fabricated tools and technologies to construct the bridges, and transform offshore construction into land construction as much as possible to reduce the impacts on *Sousa chinensis*; Combine multiple environmental methods in the large-scale offshore construction to protect *Sousa chinensis*; Strengthen the environmental awareness of construction entities and implement reasonable environmental protection measures by prohibiting illegal disposal to the seas; Arrange the construction schedules, such as channel dredging and base groove excavation during tidal periods of weak hydrodynamics, and minimize the influence on marine resources; Optimize the project schedule by avoiding construction during spawning; and Strictly control construction vessels at sea and provide a buffer space for *Sousa chinensis* habitats at the end of construction.

(2) Introduce considerable energy and material inputs to resource environment subsystems and improve the original ecological structure and food chain, and improve the food

Table 3 Survey on *Sousa chinensis* for the Hong Kong-Zhuhai-Macao Bridge IMP (2005–2016)

Time	Phase	Investigation
Feb. 2005–Jan. 2006	Engineering feasibility study stage	Conduct *Sousa chinensis* and fishery resource survey
Aug. 2010–Jan. 2011	Before the main construction project	Conduct *Sousa chinensis* and fishery resource background investigation and evaluation
2011–present	During the construction on the main project of the bridge	Conduct the monitoring of *Sousa chinensis*
Aug. 2015–Aug. 2016	Construction of mid	Conduct a mid-term investigation and assessment of *Sousa chinensis* and fishery resources

quality of *Sousa chinensis* through the following: scale and intensity of fishery resources are increased, several high-quality bottom fish species are released, and the composition of fishery resource structure is optimized.

(3) Provide information support for the human control mechanism of the social subsystem through continuous investigation and detection, including the optimization of monitoring and analysis methods, improvement of monitoring information accuracy, and maintenance of dolphin and fishery resource investigation and monitoring by restoring the functional areas of protected areas and by providing information flow support, especially after the completion of construction.

6 Conclusions

The management activities of IMP should be conducted by engineering systems, but the management perspective should be extended. The coupling and evolution mechanisms across the engineering, social, economic, and resource environment subsystems of IMP should be considered to achieve sustainable development.

This study emphasized the concept of engineering integrity to overcome the common view of conventional projects being an engineering project only. We comprehensively viewed the relationship of engineering, economy, society and resource environment subsystems, which resulted in a framework and conceptualization of IMP complex ecosystem. On the basis of society-economy-environment complex ecosystem theory, the present study emphasized the special features of IMP and their impacts on the society and economy and the environment. We also ecosystem engineering subsystem as part of IMP complex ecosystem and investigated its evolution features and mechanism.

The IMP complex ecosystem can provide a framework for material, energy, and information exchanges across engineering, economy, society, and resource environment subsystems, which in turn can serve as basis for structure, function, and coupling mechanism research.

The IMP complex ecosystem is regarded an engineering -social-economic-resource environment complex ecosystem, in which the engineering subsystem is the core, the resource environment subsystem is the foundation and the condition, the social subsystem is the base, and the economic subsystem is the leading factor. These four subsystems are interdependent through material circulation, energy flows, information transmissions, and value transformation activities. The social, economic, and resource environment subsystems are dominated by information flow, material flow, value flow, and energy flow, respectively.

The IMP complex ecosystem has self-organization and typical hetero-organization characteristics. Therefore, the evolutionary process has similar development mechanisms on the ecosystem with self-organization capabilities. The IMP complex ecosystem in this study showed a ladder-like upward trend due to human intervention and regulation behavior. A positive evolution of the system can be ensured by maintaining system development, introducing negative entropy, and using negative entropy to integrate human controls.

The complex ecosystem theory is adopted for the management activities of the Hong Kong-Zhuhai-Macao Bridge, especially for the protection of *Sousa chinensis*, which completely accounted the leading role of information flow of the social subsystem. Through continuous flows of information support, the entropy activities of the social and economic subsystems are reduced to the resource environment subsystem. Moreover, a number of negative entropy factors are introduced to the resource environment subsystem, and the support of information to achieve the protection of *Sousa chinensis* and sustainable development of Hong Kong-Zhuhai-Macao Bridge as a whole is achieved.

To our knowledge, this study is the first of many published works to define IMP complex ecosystem and describe related content and framework. Future work is advocated to intensively explore coupling patterns and relations, especially the coupling relations of different IMP. Other case studies should be conducted to enrich the theoretical framework.

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