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Avoiding the innovation island in infrastructure mega-project

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Abstract Infrastructure mega-project (IMP) innovation is a complex process characterized by highly diverse innovators, a dynamic life-cycle, and stickiness of innovation knowledge. The IMP's innovation network can be easily broken due to the fact that the network involves many different innovators across different industries and different projects. Further reasons for the fragility of the IMP's innovation network are the dynamics of the IMP life-cycle, the diversity of the IMP's innovative entities, the uniqueness of each IMP, and the temporary nature of each IMP's organizations. The *innovation island* formed by the breaking of an IMP's innovation network can stifle and harm innovation performance. Drawing from the knowledge-based view as well as innovation network theory, our research identifies the heterogeneous characteristics of IMP innovation. We propose a framework to analyze the formation mechanism of the IMP innovation island from three dimensions—the *horizontal innovation island*, the *vertical innovation island*, and the *longitudinal innovation island*. We look at the Hong Kong-Zhuhai-Macao Bridge project to elaborate the innovation island concept that negatively impacts IMP innovation. We also offer theoretical implications regarding the broader question of how IMPs can manage their innovation in practice.

Keywords innovation in mega-infrastructure projects, the diversity of innovation bodies, life-cycle dynamics, the unique and temporary nature of IMPs, innovation island

1 Introduction

The term infrastructure mega-project (IMP) refers to those basic infrastructure projects that involve large-scale investment, a long term of construction, the complexity of uncertain elements, heterogeneous stakeholders, and a tremendous impact on the ecological environment (Lin et al., 2017b; Ma et al., 2017; O'Connor et al., 2015; Ozorhon et al., 2015; Qiu, 2007; Zeng et al., 2015). Examples of IMPs include the Channel Tunnel between France and England, the Three Gorges Dam project in China, and the Hong Kong-Zhuhai-Macao Bridge (HZMB) project. Ruiz-Núñez and Wei (2015) argue that emerging and developing countries would almost double their current spending from 2014 to 2020. Duvall et al. (2015) predict that the world needs to spend almost 57 trillion USD on new infrastructure over the next 15 years. Both studies suggest that the potential market for infrastructure development is growing around the world. To facilitate the smooth running of their IMPs, organizations must innovate to solve complex construction problems and achieve the basic goals set by the various stakeholders.

What is IMP innovation? IMP innovation comprises the innovative activities based on innovation demands among different organizations accommodated in IMPs (e.g., owners, designers, contractors), aimed at providing the whole solution for projects to achieve multiple goals (Gann and Salter, 2000). It is now necessary to reconsider innovation in the context of mega-construction projects to explain which factors can influence and impact their success.

IMPs are technologically complex, with high costs, high quality standards, and stringent environmental requirements (Brookes, 2014; Priemus et al., 2008; Qiu et al., 2017). Compared with general construction projects, the

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construction methods of IMPs have transitioned from the traditional site-construction methods to pre-industrialized production or rapid manufacturing approaches (Buswell et al., 2007; Davies et al., 2009; Larsson et al., 2014). For example, the Snøhvit LNG project in Norway, the Pluto LNG project in Australia, and the Hong Kong-Zhuhai-Macao Bridge in China, are using pre-industrialized production approaches. Second, the innovative entities in IMPs have expanded from the traditional actors (e.g., designers, contractors, owners) to add new innovative service providers (Chung et al., 2009), including major equipment manufacturers, new material suppliers, information technology service providers, meteorological and hydrological institutions, and satellite service providers. The relationship among all these actors is dynamically embedded and varies based on the different stages of the project life-cycle. Third, the industries involved in IMP construction have span the traditional construction industries but also include other industries (He et al., 2015a), such as equipment manufacturing, energy saving, environmental protection, and finance. For example, the construction site of the Hangzhou Bay Bridge is located at one of the strongest tidal gulfs in the world, with extremely complex environmental conditions such as the tidal range, tidal current, deep erosion, strong corrosion. However, the soil layer of the Hangzhou Bay contains natural gas, increasing the possibility of explosion during construction, not to mention the fact that this can exacerbate the erosion of the bridge foundation. What's worse, engineers have never encountered these conditions before, and there is no similar past experience from which they can learn. The engineers invited experts from oil companies to join their group to successfully create a new construction method—the deflation of gas under control—to solve the potential hazards of natural gas for the bridge construction and the stabilization of the bridge foundation. Hence, IMP innovation requires not only innovative entities from different departments, different organizations, and different industries to engage in cooperative innovation to achieve the IMP's goals, but also the successful building of unified innovation networks to manage the transfer of knowledge and information among the different innovative entities (Kale and Ardit, 2010; Keast and Hampson, 2007).

Compared with traditional corporate innovation, IMP innovation highlights the importance of combining technical expertise from other organizations and other industries in order to satisfy their innovation demands through the whole life-cycle of IMPs (Brockmann et al., 2016; Gann and Salter, 2000). For example, information and communication technology (ICT) promotes the intelligent construction, operation, and maintenance of engineering (Chung et al., 2009; Shi et al., 2017). New materials and inputs lead the innovation of engineering design and products (Ozorhon et al., 2015). Numerical control technologies drive the adoption of new construc-

tion technologies (Mitropoulos and Tatum, 1999). All these technologies come from different industries and are integrated into IMP innovation performance.

Yet anecdotal evidence abounds with examples of mega-project entities are engaged in vigorous interactions with each other, including different construction companies, research institutions, consulting companies and other manufacturing companies during the whole life-cycle. In fact, the existence of innovative entities cannot ensure the abilities for mega-project team to innovate. The tight embeddedness among different innovative entities requires all kinds of entities to engage in innovative activities, forming a whole mega-project innovative network. The innovation island can form due to the ruptures in innovation network. According to the different mechanism of being rupturing in network, there are three different types of innovation island.

First, due to the classification of disciplines across the whole life-cycle of IMPs, the innovative entities have been separated into different stages, including the concept stage, the feasibility study stage, the design stage, the construction stage, the operation stage, and so on. This separation of stages leads to ruptures in innovation networks across the different stages, an occurrence that is termed *vertical innovation island*. Second, the diversity of innovative entities increases the complexity in the structure of the innovation network, where the entities are distributed to different construction departments, different organizations, and different industries. The fragmentation among different innovative entities creates the split of innovation network, termed *horizontal innovation island*. Third, the uniqueness of each IMP and the temporality of the IMP team create barriers for knowledge transfer and organizational learning among different IMPs. The breach of the innovation network connected to distinct IMPs can create a cross-project innovation island, termed *longitudinal innovation island*.

Recent studies on innovation in the construction industry have underscored which organization-level factors influence firms' innovative strategies and innovative outcomes (Lin et al., 2017b; Manley et al., 2009). One study describes how to successfully adopt technological innovation in the construction industry (Davies et al., 2009). Most of the studies are focused on the organization level (Barlow, 2000; Davies et al., 2009; Gann and Salter, 2000). There have been few, if any, systematic efforts to investigate how innovators and the structure of an innovation network influence mega-project innovation performance (Barlow and Köberle-Gaiser, 2009; Davies et al., 2009; Keegan and Turner, 2002). This paper, focusing on IMP innovation, attempts to explain how the dynamics of the project life-cycle, the diversity of innovative entities, the uniqueness of each IMP, and the temporality of project organizations influence the formation of innovation islands in IMPs, which is detrimental for innovation performance. We propose a framework to

analyze IMP innovation, and we introduce flexible innovation strategies to build connections that counter innovation islands in IMP innovation networks.

The remainder of this study is organized as follows: We first review the limited empirical literature on innovation in construction management. Next, we identify the characteristics of IMPs. In the third section, we develop a theory on the formation of IMP innovation islands and we offer hypotheses. In the fourth section, we discuss a solution that builds bridges between innovation islands.

2 Literature review

A large body of literature has largely focused on corporate innovation in construction industries (e.g., Blindenbach-Driessen and van den Ende, 2006; Bossink, 2004; Eriksson, 2013; Keegan and Turner, 2002; Larsson et al., 2014; Manley et al., 2009). These researchers found that construction-specific attributes impede motivation in the construction industry (Arditi et al., 1997; Keegan and Turner, 2002). Some scholars also explain that the driver of construction innovation can come both from internal organizational factors and the external environment (Barrett and Sexton, 2006; Manley et al., 2009; Rose and Manley, 2012). Researchers have shown that environmental pressure (Bossink, 2004), technological capability (Gann and Salter, 2000), knowledge exchange (Eriksson, 2013), leadership and owners' cognition of their construction companies (Barrett and Sexton, 2006; Ozorhon et al., 2014), and ownership structure (Miozzo and Dewick, 2002) are drivers of construction innovation. Drawn from the corporate governance perspective, research by Miozzo and Dewick (2002) differentiates strategic innovation from operational innovation in construction companies, and finds that ownership, management structure, internal mechanisms of knowledge transfer, and external paths for gaining outside resources all impact construction innovation. Manley et al. (2009) sampled 1300 firms in the construction industry to demonstrate that marketing strategies are the least important differentiators of innovation performance—less important than employees, technology, knowledge, and relationship strategies.

Scholars have also found that many factors impede corporate innovation in the construction industry (e.g., Davies et al., 2009; Gann and Salter, 2000; Keast and Hampson, 2007). These factors include the high value of precision and accuracy required (Keegan and Turner, 2002), the institutionalization of project management knowledge in IMP management (Keegan and Turner, 2002), the lack of an integration mechanism (Davies et al., 2009; Eriksson, 2013), and firm-specific innovative capabilities (Manley, 2008). These studies show that, different from manufacturing industries, the construction industry's fragmentation and discontinuity of projects

negatively impacts organizational learning, knowledge transfer, and technological absorption (Engwall, 2003; Gann and Salter, 2000; Keast and Hampson, 2007), all of which impede organizational innovative outcomes.

There are also many studies on construction innovation at the project level, as shown in Table 1.

Only a few studies have investigated how the innovation island works in the whole innovation network (Engwall, 2003; Keast and Hampson, 2007; Ruef, 2002). Drawing on social network theory, Ruef (2002) explains how the island among entrepreneurs' social networks impacts firm innovation, and finds that the island restricts their communication with certain people. This is called a *communication island*. Ruef argues that the island in entrepreneurs' social networks can drive more innovation than other kinds of social network ties. Engwall (2003) draws from project management to explain how the interior processes of a project are influenced by its historical and organizational contexts, and argues that the project should not be treated as an island, because the unique project missions still have non-unique technical components and highly standardized administrative procedures. Engwall's findings suggest that the experiences and knowledge from the existing IMPs should be transferred into other newly-built IMPs or to IMPs that are under construction; this could reduce the uncertainty and improve the productivity and efficiency (Engwall, 2003).

In the literature, the rupture of the innovation network and the concept of innovation island have received less attention, yet these issues are critical for IMP managers to manage their innovation. Based on our review of the innovation network literature, this paper proposes a framework to analyze three dimensions of the innovation island in IMPs, and introduces the idea of flexible innovation in IMPs to build bridges among the different innovative entities.

3 Innovation in IMPs

The term *innovation* refers to a new or significantly improved product, service, process (e.g., production), marketing activity (e.g., promotion, pricing strategies), or management process (Mortensen and Bloch, 2005). However, innovation in IMPs is totally different from traditional corporate innovation. IMP innovation is parasitic on IMP, and with definite innovation demands to pursue, while corporate innovation is focused on the organization-level, and correlated with vague innovative outcomes. For IMP innovation, constellations of innovative entities with different competencies and specialties (e.g., designers, main contractors, subcontractors, material and component suppliers, information service providers, consultants) are required to participate in different stages,

Table 1 Research on construction innovation at the project level

No.	References	Research method	Conclusions
1	Barlow (2000)	Case study	Barlow analyzes the Andrew Alliance construction project and finds that appropriate tools and techniques for integrating supply chain members, such as a partnering relationship, can result in technical and process innovation.
2	Davies et al. (2009)	Case study	The authors analyze the London Heathrow Terminal 5 project and propose a systematically integrative model to explain how organizations innovate to improve firm performance. They find that organizations can build in-house capabilities and use the knowledge gained during the implementation of a breakthrough project to improve performance.
3	Barlow and Köberle-Gaiser (2009)	Case study	The authors analyze hospital construction projects and find that the Private Finance Initiative (PFI) reduces construction risk and improves project reliability, but can stifle design innovation.
4	Barlow and Köberle-Gaiser (2019)	Case study	The authors analyze the London Heathrow Terminal 5 project and propose a decision model of new technology adaptation for mega-projects. They also identify three factors, namely attitudes toward risk, politics, and (lack of) established standards.
5	Ozorhon (2013)	Case study	Ozorhon considers four construction projects and proposes a framework to explore the various components of innovation. Ozorhon finds that environmental sustainability is the main driver of innovation, and that collaborative working among team members and strong commitment can enable innovation, but that reluctance, inexperience, and cost are the main barriers to innovation.
6	Eriksson (2013)	Theoretical development	Eriksson finds that the temporary nature of a project, the decentralization of its organizational structure, and the lack of an integration mechanism can impede organizational ambidexterity. Eriksson proposes that cooperative procurement can solve the innovation paradox.
7	Rose and Manley (2012)	Case study	The authors analyze Australian road infrastructure projects and find that six factors—namely project goal misalignment, client pressures, weak contractual relations, lack of product trialing, inflexible product specifications, and product liability concerns—are the main obstacles in Australian road projects.
8	Roumboutsos and Saussier (2014)	Theoretical development	The authors find that the private party in a PPP arrangement can positively influence organizations in their investment in low-risk incremental innovations.
9	Davies et al. (2014)	Case study	The authors analyze London's Crossrail suburban railway system and identify four intervention stages to generate, discover, and implement innovation in a megaproject: The bridging window, the engaging window, the leveraging window, and the exchanging window. They propose that a coordinated mobilization of the innovative capabilities across the project supply chain was the key to the successful megaproject's innovation.
10	Brockmann et al. (2016)	Case study	The authors analyze the BangNa Expressway in Thailand, and find the megaproject innovative. They propose that megaproject innovation is systematic and not necessarily positive.

choosing the right combination of innovation paradigms (e.g., cooperative innovation, integrative innovation, open innovation) to engage in different innovative activities to achieve IMP innovation goals.

However, the IMP is characterized by a high level of complexity. Complexity is described as a property of a project that makes it difficult to understand, foresee, and manage, even when given reasonably complete information about the project system (He et al., 2015b; Vidal et al., 2011). It has been acknowledged that the complexity of IMPs includes task complexity, technological complexity, organizational complexity, environmental complexity, and cultural complexity (Brockmann et al., 2016; He et al., 2015a; Luo et al., 2017). Due to these different dimensions of IMP complexity, the innovation system of IMP is also

characterized by a large scale of complexity, which includes the diversity of innovative entities, life-cycle dynamics, the uniqueness of the IMP innovation system, and the temporary nature of the IMP project organization.

3.1 Diversity of innovative entities

The fact that IMPs are huge and have long life-cycles means that IMPs often have large-scale innovation networks, which are involved in different innovative entities at the different stages of the life-cycle. Innovative entities in IMPs tend to be cross-sector, cross-organization, cross-industry, and even cross-border, showing a high diversity of entities. The complexity of the IMP's environment and technologies makes it impossible for

only one single organization, without absorbing other new knowledge and information to achieve the project goals and to satisfy the innovation demands (Gann and Salter, 2000). It requires that the owners—termed *system integrators* by Davies et al. (2009)—jointly connect designers, contractors, research institutions, consultants, and other innovative entities to form a close diversified innovation network, through which innovation knowledge, resources, and information can be transferred (Barlow and Köberle-Gaiser, 2008; Burt, 2004). A tightly connected but diversified network allows innovative entities to successfully implement their own ideas and plans for the IMP innovation.

Compared to other industries, the engineering-specific attributes of IMPs impede the flow of innovation resources among an innovation network—This includes engineering accuracy, technical reliability, and technical effectiveness (Barlow and Köberle-Gaiser, 2008; Eriksson, 2013; Keegan and Turner, 2002). However, new technology is often uncertain, and the engineering culture in the engineering industry will hinder significant flow in engineering innovation knowledge (Barlow and Köberle-Gaiser, 2009; Keegan and Turner, 2002). At the same time, the knowledge structure of project management, which is deeply rooted in construction industries, has led to the institutionalization of constraints such as duration, quality, and safety, rendering the construction innovation inert and weakening the flow of innovation resources (Keegan and Turner, 2002).

Moreover, the distrust and lack of cooperation among different innovative entities can impede innovation in IMP. For example, Barlow (2000) proposes the *partnering mode* to reduce the risks to innovation in complex offshore construction projects, to increase their trust with different innovative entities, and to help to strength their organizational learning, which is aimed to improve their cooperation among organizations. Recent studies also show that the public-private partnership (PPP) model can build a potential mechanism to help actors in infrastructure projects to engage in cooperative activities in the planning, design, and construction stages, increasing innovation performance (Barlow and Köberle-Gaiser, 2009; Rouboutsos and Saussier, 2014).

IMPs cover a large body of innovators, which would be a big challenge to build a good innovation network to promote the knowledge flow and information transfer among multiple innovative entities. However, the engineering knowledge is always sticky, which means it is costly to transfer knowledge from its point of origin to a specified problem-solving site in the whole innovation network (Dodgson et al., 2007; von Hippel, 1994). The stickiness of innovative knowledge make it more difficult for innovative entities to transfer their own experiences and knowledge among a large innovation network, because of the uncertainty of technological innovation and the

unpredictability of future return. Thus, the large volume of innovators among IMP innovation networks can increase the difficulty and costs of knowledge transfer among innovation networks.

3.2 Dynamics of the life-cycle

The major innovative actors located in the center of the network in one stage of the life-cycle can evolve to be located into other parts of the innovation network, leading to a highly dynamic life-cycle (Park et al., 2004). If the innovative actors are at the center of the innovation network, it means that they are more engaged in the major innovative activities than the other actors in the network. The evolution of innovative entities means that the main innovative activities have been transformed from actors to other actors during the different stages of the whole life-cycle. For example, during the design stage, the designers and consultants are at the center of the IMP's innovation network and are responsible for the main design innovations, absorbing other new technologies and knowledge to improve the quality of the design. In the construction stage, the contractors and construction companies are at the center of the IMP's innovation network, and are the main innovative entities engaged in the improvement of construction technologies and the installation of engineering. Hence, the innovative entities evolve during the different stages of the IMP life-cycle, making knowledge transfer and absorption more complex, and increasing the possibility that innovation islands will form among the various innovative entities. Different innovative entities are necessary during the different stages of the project life-cycle, but each one has important information to bring.

Moreover, the separation of stages within the life-cycle creates disparate channels for the transfer of information, disrupting the flow of feedback between the various innovative actors to support their innovative activities, which is essential for the success of the IMP (Larsson et al., 2014). For example, the designers create a unique design plan for the IMP, resulting in a large increase in the technological complexity and construction costs. The construction contractors should provide information and feedback to the designers so that they all can discuss how to cooperatively improve the innovation performance in the design phase with the goal of reducing the technological complexity and improving the project performance. Due to the absence of contractors in the design phase, the knowledge of contractors cannot be transferred through the innovation network and to the various designers, which is essential for the improvement of innovation performance (Eriksson, 2013; Gann and Salter, 2000). The innovative activities are interactively influenced by each other, showing a high level of velocity on the changes in their innovation network during the different stages.

Third, the dynamic life-cycle decreases the motivation

of innovative entities among IMPs to drive for innovation in design and engineering organizations (Eriksson, 2013; Gann and Salter, 2000; Larsson et al., 2014). Recent studies have shown that innovation in IMPs often needs several organizations to cooperatively struggle for the innovative activities (Davies et al., 2009; Davies et al., 2014; Gann and Salter, 2000). However, working in large teams makes it difficult for all the organizations to define their own responsibilities and rights for the IMP innovation. On one hand, the blurry boundary of the actors' innovative activities delays their participation, lowering the motivations for innovation in the IMP innovation network. For example, the desperation of the design and construction stage can delay the contractors' activities in the IMP innovation network, lowering the motivation of the contractors' innovation for design activities (Eriksson, 2013; Larsson et al., 2014). On the other hand, the large team size in IMPs makes it difficult for innovative entities to distinguish intellectual property among different actors, which is a key factor that drives innovation for individual organizations (Gann and Salter, 2000). The clear definition of intellectual property can help construction firms to gain more value from their innovative activities. However, some innovative activities that take place are hard to price and poorly measured, lowering the already low motivations for innovation in IMPs (Gann and Salter, 2000), such as design activities. Different innovative entities perform differently in the innovation network at the different stages of the life-cycle, showing the highly dynamic life-cycle among IMPs. These dynamics can impede the formation of a close-knit innovation network, and disrupt knowledge and information flows, thereby lowering the motivation for IMP innovation.

In sum, innovation in IMPs involves a system that is complicated by the complexity of innovation environments, the diversity of innovative entities, the dynamics of the IMP life-cycle, the radicalness of new technologies, the stickiness of IMP knowledge, and the integration of IMP technologies. These internal and external factors interactively influence innovative activities in IMPs.

3.3 The unique nature of the IMP and the temporary nature of the IMP team

An IMP is a unique product, with complex processes (Davies et al., 2009; Davies et al., 2014). Some scholars argue that the processes for megaproject construction can be divided into progressively standardized, simplified, and repeated production approaches to improve performance (Davies et al., 2009). However, there are many technologies that are needed to be renewed or created to solve the complex situations that occur during megaproject construction. These offer great opportunities for project actors to innovate and develop their learning capacities, but also hamper the innovative spillover across IMPs because of

the technological incompatibility among the different IMPs.

Moreover, IMPs are often created and built by a temporary alliance of disparate organizations with distinct social-political contexts (Slaughter, 1998). After the successful implementation and delivery of an IMP, the IMP team is dissolved. Unlike the traditional manufacturing innovation system, the IMP activities are often split into planning, design, construction, commissioning, and operation activities among many different parties. During the different stages of the megaproject, the temporary IMP team evolves through the whole life-cycle. Due to the temporary nature of IMPs, the team composition of material suppliers, designers, contractors, and other project actors is often not repeated in future IMPs, even when the IMPs are extremely similar. In sum, IMP innovation has been affected by the unique and temporary nature of the IMP, the actors of which come from different departments, organizations, and industries.

4 Decoupling of the IMP innovation island

Innovation resources are found in tremendous innovative entities, which are scattered across different individuals, organizations, industries, and countries. To achieve their goals for innovation, IMPs' innovative entities are required to form a unitary innovation network, allowing the innovation resources to transfer between entities. The diversity of the innovative entities, the dynamics of the life-cycle, and the uniqueness of each IMP and its temporality can easily result in the rupture of the innovation network, which is harmful to the IMPs' innovative activities (Davies et al., 2009; Engwall, 2003). Thus, the IMP's innovation network is separated vertically by the different disciplines, separated horizontally by the different stages of the IMP life-cycle, and separated longitudinally across different IMPs, resulting in the formation of the IMP innovation island (Engwall, 2003; Gann and Salter, 2000; Sheffer and Levitt, 2012).

4.1 The vertical innovation island

A vertical innovation island occurs when the innovation network is vertically ruptured by stages (e.g., the planning, design, construction, commissioning, operation, and maintenance stages). As shown in Fig. 1, there is a rupture in the link between the main innovative entities at the different stages, which leads to the formation of a vertical innovation island. The discontinuity of the different stages in the IMP life-cycle disrupts knowledge flow and is harmful for various innovative activities.

How does a vertical innovation island stifle innovation in an IMP? First, we argue that a vertical innovation can impede the flow of knowledge among the different

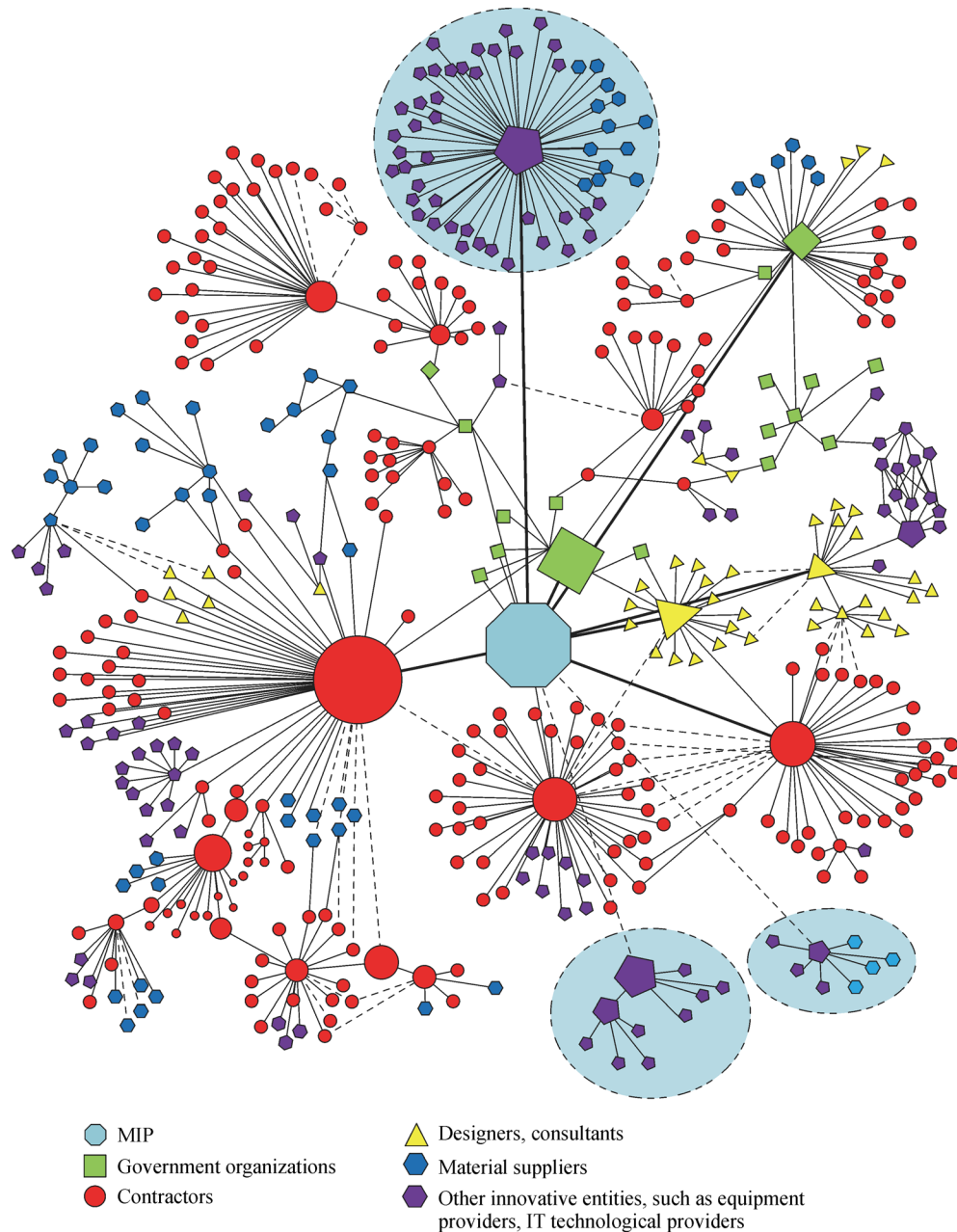


Fig. 1 Horizontal innovation island

innovative entities in the different stages, which hampers the rapid assimilation of new knowledge and organizational learning for both contractors and designers (Eriksson, 2013; Salter and Torbett, 2003). For example, when the design-bid-build model is adopted for an IMP, the work of design and the work of construction are separated. Designers and consultants are often involved in the conceptual and design stages, while contractors are engaged in the construction stage. Divorce of the design stage from the construction stage can result in a barrier to innovation, because the contractors' construction knowledge is left out of the design work, whereas if it were

included, buildability could be enhanced and innovation performance could be improved (Eriksson, 2013).

Second, the vertical rupture of the network can also stifle the exploitation of knowledge among the different innovative entities (Gann and Salter, 2000). This "black box" of the knowledge pool in IMPs can reduce innovation performance. On the other hand, due to the restrictions of the engineering environment and the requirements for quality and safety, contractors are less motivated to engage in innovative activities to improve the feasibility of design in the construction stage, which might be more costly.

Third, the vertical island hinders knowledge integration,

which is critical for successful project delivery (Barlow and Köberle-Gaiser, 2009; Gann and Salter, 2000). IMP innovation is usually regarded as a complex innovation system, with a large number of innovative entities, a high level of technical uncertainty, and a huge, complicated innovation environment (Davies et al., 2009; Pellicer et al., 2014; Rose and Manley, 2012). The emergence of new knowledge and technologies is leading IMP construction into a potentially large systematic integration of innovation, increasing the complexity of IMP innovation (Davies et al., 2009; Gann and Salter, 2000; Ozorhon, 2013; Ozorhon et al., 2014; Rose and Manley, 2012). These new technological innovations integrated from other industries could change the construction methods, the project planning, and the project design.

In sum, the formation of a vertical innovation island can impede IMP innovation, which is harmful for knowledge flow, knowledge assimilation, organizational learning, knowledge exploitation, and technological integration.

4.2 The horizontal innovation island

A horizontal innovation island is a separation of firms and individuals into different groups by discipline or area of expertise (e.g., meteorological units, satellite navigation units, engineering machinery, structural engineering, and civil engineering) (Barlow, 2000; Sheffer and Levitt, 2012).

An IMP is a complex, systematic project, which requires many actors to cooperatively engage in innovative activities and provide necessary technologies to meet the innovation demands (Davies et al., 2009; Davies et al., 2014; Lin et al., 2016; Lin et al., 2017b; Ma et al., 2017; Zeng et al., 2015). In an IMP innovation network, the major innovative entities present a highly competitive, dynamic, and fragmented status (Barlow, 2000), which generates a barrier to innovation and blocks the flow of knowledge among the innovative entities.

Moreover, the innovation resources are scattered among the various innovative entities, and can be fabricated into IMP innovative outcomes with effective integration. Construction companies tend to specialize in one field, because of the complexity of construction technology and the requirement of a large amount of domain-specific knowledge. The formation of an IMP innovation island obstructs their collaborative innovation activities, curbing the ways that innovative entities can communicate. Because construction technology is so complex and requires such a vast amount of domain-specific knowledge, construction firms tend to specialize in one trade.

The lack of effective communication exchange is illustrated in the schematic diagram of Fig. 2. For example, due to the requirements of engineering quality and safety standards, major projects must use new materials and new processes to meet engineering needs, but there is a barrier between the suppliers of the new engineering materials

needed and the engineering/technical team. The innovation island hinders major engineering and technological innovations.

4.3 The longitudinal innovation island

A longitudinal innovation island occurs when the experience and knowledge from previous projects cannot be transferred to subsequent projects due to the temporary nature of the projects. This experience and knowledge from previous projects are essential and beneficial for the performance of future projects (Engwall, 2003; Sheffer and Levitt, 2012). The presence of short-term, discrete IMP innovation networks complicates the flow of knowledge and innovation between organizations, often resulting in discontinuity of knowledge transfer among the different projects. If the knowledge gained and solutions developed from previous successful IMPs' practices cannot be diffused to subsequent projects, there exists a large knowledge gap among the different innovative entities. Hence, innovation and organizational learning are all hindered by the discontinuous, project-based nature of IMPs, forming a longitudinal innovation island. The details of longitudinal innovation island have been shown in Fig. 3.

The discontinuity of the IMP innovation network and the temporary nature of the IMP team have detrimental implications for knowledge transfer and cross-organizational learning (Eriksson, 2013). Widén and Hansson (2007) find—in their study based on 20 Swedish projects—that the level of innovation diffusion varies considerably due to the different levels of external lateral communication, vertical communication, and external integration among project organizations. Smyth (2010) finds that most innovations were successful at the project level, but not across the firm or sector in terms of knowledge transfer and innovation diffusion based on 150 demonstration projects in the UK's "Continuous Improvement" program. This might be because of the uniqueness of each IMP and the temporary nature of each project team. The lack of an industrial professional network in the construction industries brings with it the risk of IMP teams being disconnected from other innovative entities who are working on similar IMPs. Hence, the short-term project focus has a detrimental impact on knowledge discussions and cross-project organizational learning, which in turn hampers the innovative spillover effect among the construction industry (Dubois and Gadde, 2002; Pemsel and Wiewiora, 2013).

Knowledge related to IMP construction can also be classified as explicit or tacit (Polanyi, 1996). Explicit knowledge can be easily codified and transferred from one entity to another, while tacit knowledge is difficult to articulate and access because it is usually developed based upon experiences, actions, feelings, and so on (Salter and Gann, 2003; Yuventi et al., 2013; Zeng et al., 2015). Many

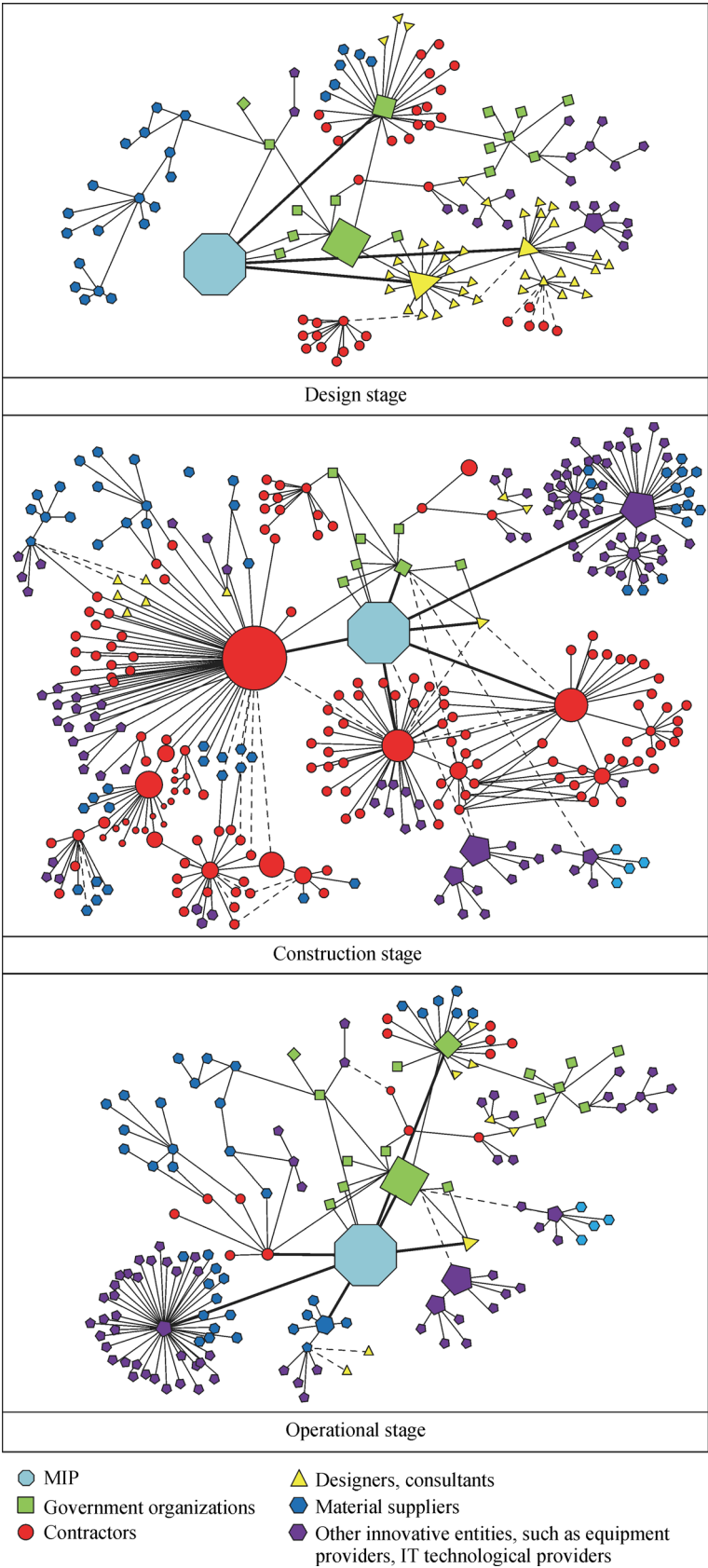


Fig. 2 Vertical innovation island

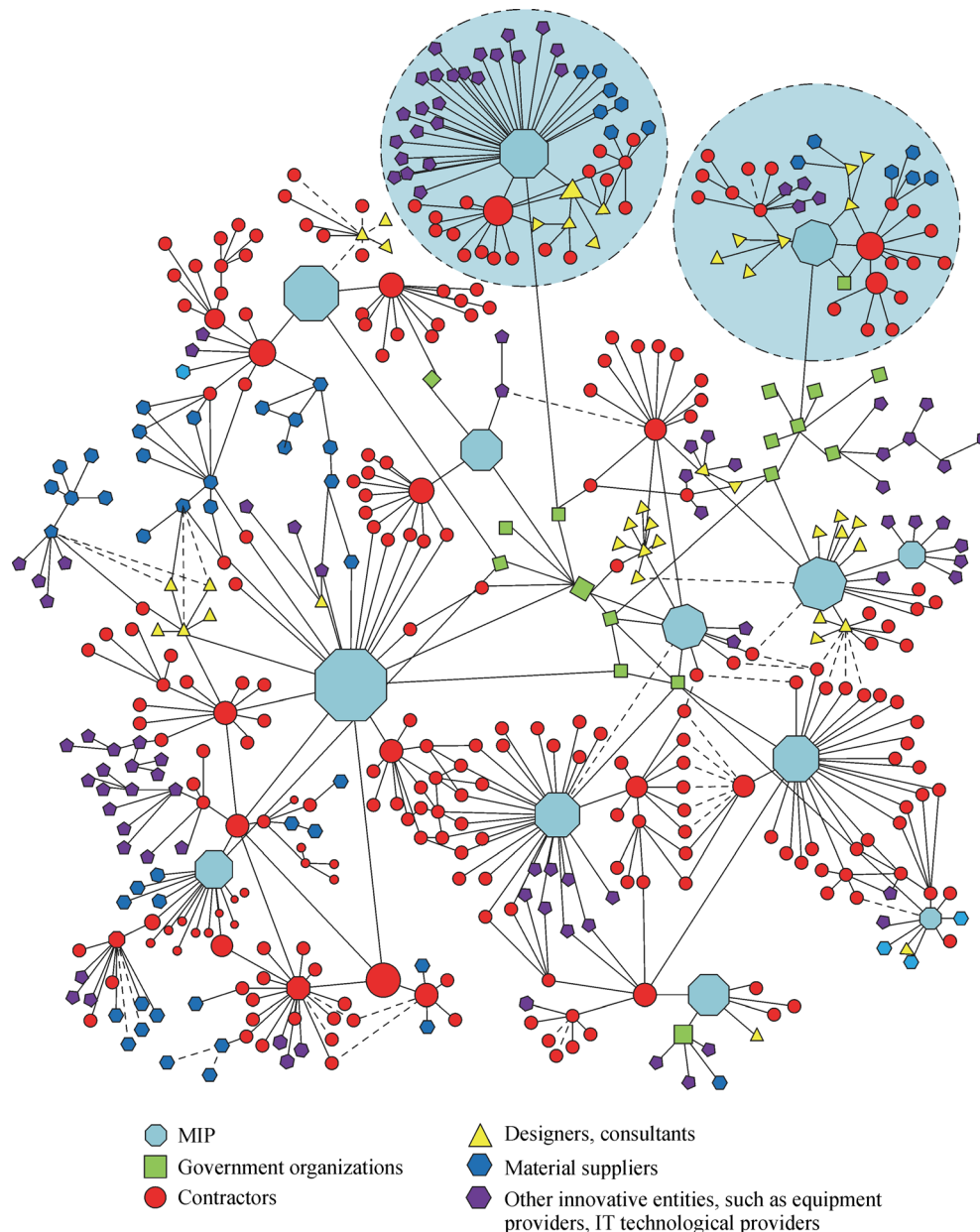


Fig. 3 Longitudinal innovation island

of IMPs' technological experiences involve tacit knowledge, and also sticky information, which is harder to transfer among the different project teams. Under these circumstances, coordination and integration of knowledge across organizations is critical for the success of IMPs (Barlow, 2000). Although the development of non-hierarchical communications structures across organizations, the presence of system integrators within project teams, and the integration of repetitive business processes can decrease the possibility of rupture in an innovation network (Barlow, 2000; Davies et al., 2009), in terms of innovation across different IMPs, IMP project teams cannot fully benefit from the experiences of former

successful IMPs within the current industrial structural solution (Eriksson, 2013).

5 Case study

The current research was based on a single case study of the HZMB project, situated at the Pearl River Estuary of the Lingdingyang Sea. HZMB is an IMP that consists of 29.6 km of dual three-lane carriageway in the form of a bridge structure, a tunnel of about 6.7 km, and two artificial islands. HZMB links the Hong Kong Special Administrative Region (HKSAR), Zhuhai City of Guangdong

Province, and the Macao Special Administrative Region in China. The estimated investment of the HZMB project for the bridge and sea tunnel part was about 38.1 billion CNY (according to the Ministry of Transport, based on preliminary design approval of the main project). The project's capital is 15.73 billion CNY, of which 7 billion CNY is from the Chinese mainland government, 6.75 billion CNY from the Hong Kong government, and 1.98 billion CNY from the Macao government.

An inductive research approach was used, iterating between empirical findings and concepts, to draw inferences about how an innovation island is formed. We recognize the difficulties of building theory from one case study, and suggest that the framework be treated as a proposition. Multiple case studies and surveys on IMP innovation are needed for further rigorous testing and refinement. The HZMB case was selected because we had unusual research access to explore a significant phenomenon, providing conceptual insights about how two different organizations learn and innovate to improve megaproject performance. The research explored how an innovation island formed within the IMP's innovation network, and used the project's experiences to improve megaproject innovation performance. We gathered research data through observations, online reports (HZMB Authority and other patent or innovative website related to mega-projects), archival records, and interviews with senior managers on the HZMB project.

5.1 IMP innovation in the design and construction stages

The natural environment for the HZMB project was much more complex and sensitive, and had higher environmental protection standards, than other cross-sea bridges. The HZMB project's combination of a bridge and a tunnel meant that its design was unique compared with other cross-sea bridges. The HZMB project, built across the mouth of the Pearl River Delta in the Lingdingyang Sea, faced numerous typhoons and other aspects of the harsh environment. Moreover, the construction site was close to the Hong Kong International Airport, which has strict height restrictions due to aviation requirements, making the highest altitude allowed 120 m. Moreover, the HZMB project spans the shipping channel of the Lingdingyang Sea, which meets the shipping needs for 300000 t of shipping annually. The traditional design for this project was to take the bridge design for the whole project, considering the aviation restriction and the shipping conditions. If this project takes into consideration shipping demands, the height of the bridge would be 200 m—much higher than the aviation restriction. If the design were lower than 120 m, however, the bridge would be a disaster for the shipping channel. Moreover, the traditional design for a cross-sea bridge would be hard to implement in the HZMB project, because the bridge piers would exceed the upper limit of the water resistance ratio. For all these

reasons, the engineers had to come up with a non-traditional building design for the HZMB project, encompassing 6.7 km of tunnel and 22.9 km of cross-sea bridge.

To build the tunnel and bridge, it was necessary to find an island connecting the bridge and the subsea tunnel. Since there were no nearby islands available for this purpose, the project required the building of artificial islands to connect the subsea tunnel and the bridge. The Lingdingyang Sea is a typical weak sea, with a large quantity of sediment from the Pearl River mouth being deposited into the Lingdingyang Sea every year. If the artificial island's length and width were too large, it would block the flow of sediment into the sea. Once the ratio of water resistance is higher than 10%, the sediment becomes blocked deposition, which would turn the Lingdingyang Sea into an alluvial plain in the future. If the HZMB project employed the shield method to build the tunnel, the tunnel would have to be buried deeper, and the length of the artificial island would exceed the required length. Taking into consideration the water resistance requirement, the tunnel scale, and hydrogeological conditions, the HZMB project team proposed an immersed tunnel design. The subsea tunnel of the HZMB project is made up of 33 sections of reinforced concrete tunnels. Each immersed tunnel section is 180 m long, 38 m wide, and 11.4 m high. The displacement is about 80000 t.

The construction site of the HZMB mega-project, located as it is at a major shipping channel, also faces high standards of environmental protection, because it happens to be an ecological protection zone of the Chinese white dolphin. The environmental protections, schedule restrictions, and quality reliability forced the engineers to innovate—creating a new construction plan for two artificial islands, involving many more organizations and individuals in the project, and increasing the cultural, organizational, and task complexity. The traditional ways for construction of artificial islands include dumping stone to create the cofferdam, dredging silt, and filling. However, the traditional construction methods (e.g., the riprap slopes foundation method or the conventional gravity caissons foundation method) are not available in the Lingdingyang Sea because of the thick layer of silt there. The silt would make the caissons or stones slide with gravity, making the foundation of the artificial islands unstable. Moving the silt from the Lingdingyang Sea or consolidating the silt would greatly impact the ocean environment. The HZMB project team employed a new construction method—using 120 giant, round, steel buckets—to compose the artificial islands, which is environmentally friendly and efficient for construction.

5.2 The involvement of cross-industry innovation networks

The successful construction of the artificial islands was based on the production of 120 giant steel cylinders, each weighing 550 t and measuring 55 m in height. Due to the

size of the steel buckets, there was no plate or mold available to produce these cylinders. The only way to produce them was through an assembly approach, dividing each steel bucket into 72 modules, which would bring a serious problem, exceeding the error restriction. Ultimately, the HZMB project team used an internal tank to solve the problem of precision manufacturing of the steel buckets—to create a cylindrical steel frame to support the steel stitching, meeting the error limit. Because traditional construction materials suppliers would not be able to fulfill the equipment needs for such a massive job, a heavy manufacturing company, Shanghai Zhenhua Heavy Industries Company Limited (ZPMC), undertook the work of producing these steel buckets within a limited time frame. The large volume demand of the steel buckets and the precision limit forced the producers to innovate, and it improved their competitiveness.

After the steel buckets production was completed, the project team had to transport these giant buckets from the production base, Shanghai Changxing Island, to the Pearl River Estuary site, travelling about 1600 km. To ensure the project's reliability and security, the WINI company from Japan provided information about meteorological navigation twice a day, and the BMT company from the UK provided sea wave spectrum data for sea shipping prediction. The inclusion of ZPMC, WINI, and BMT in the production and delivery processes of the giant steel buckets shows that the IMP's innovation network included organizations from other industries—in this case, manufacturing companies and information providers.

During the construction stage of the tunnel arrangement for the HZMB project, the project team encountered some of the most difficult submarine tunnel conditions. Because the working site was 40 m under the sea, the installation was subject to ever-changing winds, waves, flow, and other factors. For the quality and safety of this project, the HZMB project team had to choose a calm, smooth tide date, called the *window period*. Considering the weather, waves, complexity of the tides, and the constraints of the construction itself, the Chinese State Oceanic Administration Marine Environment Forecast Center (COAME) joined the HZMB project team, to provide marine meteorological data for forecasting the window period for the installation. Moreover, during the installation process, the project team needed a device to detect the activities of these tunnels under water, which are characterized by low-frequency, long-lasting vibration. To detect the vibration, the Beijing Great Wall Measurement Technology Research Institute (BMTR), a spaceflight company, provided a spaceflight sensor to supervise the tunnels' activities, ensuring their successful installation. The inclusion of COAME from the meteorological industry and BMTR from the aerospace industry shows that cross-industry innovative entities are critical for the success of IMP innovation.

In order to ensure the success of the HZMB project's

steel structure manufacturing, the China Railway Shanghai-guan Bridge Group Co., Ltd. (CRSBG), a subsidiary of China Railway Group Ltd. (CREC), introduced arc-tracking technology from Japanese companies and developed their own welding robot for the bridge production, which increased the quality and production capacity for the steel bridge. First, CRSBG used unified standards for the many assembly and welding operations, increasing automation and the intelligent production of the steel box girder. Moreover, to control the quality, CRSBG developed their own information management system to collect, store, and analyze the real-time welding parameters, achieving remote computer monitoring. Automatic, mass production of the steel structure not only guaranteed the quality of the bridge structure in the HZMB project, but also increased CRSBG's competitiveness, enabling the company to expand overseas. For example, both Verrazano-Narrows Bridge in the US, and the Hålogaland Bridge in Norway, have decided to use the steel bridge structure produced by CRSBG. The technological imports from other industries (e.g., the robot industry, the welding industry, and the IT industry) have helped those organizations to develop their own innovative capabilities.

5.3 The innovation island in the HZMB project

First, the HZMB project connected designers and contractors in an intense network, which largely reduced the formation of a vertical innovation island. There were two important actors in the HZMB project: The HZMB Authority, which represents three governments—of Hong Kong, Macao, and Guangzhou—and China Communications Construction Co., Ltd (CCCC), which was the leader for the implementation of the project in the design and construction stages. The HZMB Authority signed the Design-Build contract with CCCC to fulfill the main part of the construction project, the bridge and tunnel project. Due to the Design-Build contract, the design and construction stages were undertaken by the same organizations, which reduced the fragmentation of stages along the whole life-cycle. Although the innovation network revolved around the design and construction stages, the main innovative actors in the HZMB project were still within one organization. The well-functioning communication channel and the existing knowledge-flow network reduced the formation of a vertical innovation island. For example, the manufacturing company ZPMC is owned by CCCC, who was responsible for the production of the giant steel buckets. If ZPMC was not within the innovation network, the steel bucket design plan might not have been proposed or accepted by the HZMB project team because of the technological uncertainty of the steel buckets. Compared with other designs, the steel bucket design was more efficient and much more environmentally friendly, which

helped the IMP project to be completed according to schedule. Related details about participants of the main work of the HZMB project have been described in Table 2.

Second, the HZMB project team built a large innovation network, which reduced the knowledge flow and information transfer across different innovative entities. The strong connection among the diverse innovative entities from the different industries and organizations reduced the formation of a horizontal innovation island. During the tunnel installation process and the steel bucket delivery, the information from meteorological companies was needed to sustain basic processes. For example, due to the long distance from the production base of the steel buckets, the engineers needed wave spectrum data and other meteorological information to predict the date when delivery would be possible. The large demand for the giant steel buckets and the precision restrictions not only challenged the production capacities for the IMP actors, but also forced them to increase their innovative capabilities in order to satisfy the requirements for the construction of the artificial islands. Moreover, the information provider companies, the meteorological service companies, the high-tech companies, and other companies from the IT industry and robot industry helped the HZMB project team to efficiently and successfully achieve their IMP goals. The formation of a diverse innovation network across different industries reduced the formation of a horizontal innovation island, reducing the innovation barrier to a great extent.

Moreover, the HZMB project team involved more than 21 public research institutions, eight universities, and more than 500 scientific researchers, forming a multi-disciplinary innovation network. The diversity of the innovative entities made the IMP project more diverse and creative in solving the project's technological problems. To successfully complete the HZMB project, the organizations involved developed 4000-ton floating cranes, produced a deep-water gravel-leveling ship and an 80-meter deep sand compaction pile ship, and created an eight-linking-hammer steel cylinder vibration system—all of which were done for the first time to use in the bridge's construction. The connection of the diverse innovative entities increased the diversity of the knowledge pool, reducing the innovation barrier.

Third, the HZMB project team involved many engineers who had participated in a similar cross-sea bridge in China: The Hangzhou Bay Bridge (HBB). HBB is a highway bridge connecting the municipalities of Jiaxing and Ningbo in Zhejiang province. The bridge crosses the Hangzhou Bay in the eastern coastal region of China. The major contractors and the designers of the HBB project were subsidiaries of the CCCC, which were the main designers and contractors for the HZMB project. The technological innovation that developed from the HBB project was able to be used in the HZMB project. At the same time, at the design and the construction stages, the organizations were able to use their past experiences to avoid possible technological innovation traps. Details on

Table 2 Participants of the main work of the HZMB project

Stage	Participant	Role	Country
Preliminary design of the HZMB	CCCC Highway Consultants Co., Ltd.	Leader	China
	COWI A/S	Members	Denmark
	Arup Group Ltd.	Members	UK
	Shanghai TERT Design and Research Institute	Members	China
Project consulting of the main HZMB work	Shanghai Municipal EDI Co., Ltd.	Leader	China
	Y. LIN International Group Ltd.	Members	USA
	Holland Tunnel Engineering Consultant	Members	Netherlands
	Guangzhou MDRI Co., Ltd.	Members	China
Design and construction of artificial islands and tunnel work	China Communications Construction Co., Ltd.	Leader	China
	CCCC Highway Consultants Co., Ltd.	Members	China
	AECOM Asia Co., Ltd.	Members	USA
	COWI A/S	Members	Denmark
	Shanghai Urban Construction Group Corporation	Members	China
	Shanghai TERT Design and Research Institute	Members	China
	CCCC Fourth Harbor EIDI Co., Ltd.	Members	China
	China Railway Wuhan Bridge ECM Co., Ltd.	Leader	China
Supervision of artificial islands and tunnel work	Guangzhou PWES Company	Members	China
	Guangzhou Municipal Engineering Supervision Co., Ltd.	Members	China

Note: Information is from the HZMB Authority, and en.wikipedia.org

Table 3 Participants of the main work of the HBB project

Stage	Participant	Role	Country
Design of the HBB project	CCCC Highway Consultants Co., Ltd.	Leader	CCCC
	China Railway Major Bridge Reconnaissance & Design Institute Co., Ltd.	Members	CREC
	CCCC Third Harbor Consultants Co., Ltd.	Members	CCCC
Construction of the HBB project	China Communications Construction Co., Ltd.	Leader	CCCC
	China Railway Major Bridge Engineering Co., Ltd.	Members	CREC
	China Road & Bridge Corporation	Members	CCCC
	CCCC Second Harbor Consultants Co., Ltd.	Members	CCCC
	CCCC Third Harbor Consultants Co., Ltd.	Members	CCCC
	China Railway No. 2 Group Co., Ltd.	Members	CREC
	China Railway No. 4 Group Co., Ltd.	Members	CREC

Note: Information is from HZMB Authority, en.wikipedia.org, and baike.baidu.com

participants of HZMB project have been shown in Table 3. In this case, the past experiences were transferred from the former IMP into the HZMB IMP. This longitudinal innovation island is less likely to influence the innovation performance in the HZMB project.

6 Discussion and conclusions

Nowadays, researchers and practitioners have paid a lot of attention to the management of IMP innovation. Large-scale bridges, urban subways, express railways, and large-scale hydropower stations are prototypes of the mega-project, with strong social-economic impacts. However, the uncertainty of major engineering innovation technology, the applicability of innovation rigidity, and the complexity of the mega-project triggers the formation of innovation islands in the IMP innovation network. How do we solve the problem of innovation islands in IMP innovation networks? We propose that organizations and their managers develop flexible innovation, which is a reasonable choice of innovation paradigm for different situations, to bridge the innovation island and channel knowledge throughout the innovation network.

The complexity of IMPs makes it difficult for the upgrading of existing technology to solve engineering requirements, as well as to overcome major engineering problems through the traditional cooperation among those innovative entities. The IMP project team must form an open innovation network and implement open innovation to meet the main engineering needs. A highly open innovation network not only promotes IMP innovation, but also drives the organizations within the network to innovate more. With the emergence of new technologies, the IMP project team must actively absorb external innovation resources, strengthen their innovative cooperation, and build their innovative capacities.

IMPs are characterized by the diversity of their

innovation entities. Innovation entities take different innovative activities at different stages of the life-cycle. It is difficult for a single contractor or designer to meet the demands of major engineering technological innovation. Different innovative subjects coordinate and cooperate with each other and jointly accomplish major engineering innovation activities. Through this collaborative innovation, the different innovative elements converge to achieve synergistic expansion of innovation performance. Moreover, the dynamics of the life-cycle also restrict IMP innovation. The life-cycle dynamics require that the IMP innovation actors across different stages communicate smoothly, so as to integrate engineering technologies, innovative knowledge, and other innovative elements to form a knowledge pool. A dynamic knowledge pool can help the IMP team to successfully achieve the IMP's goals. Third, the unique nature of the IMP and the temporary nature of the IMP team also impede innovation spillover. However, engineering experiences from former IMPs can also bring a lot of tacit knowledge, which is needed for IMP innovation. So, the suitable approach for IMP teams to avoid longitudinal innovation islands is to build connections with former IMP teams.

Based on our literature review and innovation network theory, this paper analyzes the multiple factors—such as the diversity of innovation entities, the dynamic nature of IMP stages, the unique nature of IMPs, and the temporary nature of IMP teams—on major engineering innovation. This paper offers a definition of the term *IMP innovation islands*, and analyzes the formation mechanism and the heterogeneous features of the innovation islands from three dimensions—vertical, horizontal, and longitudinal innovation islands. We hope that this research can provide a new perspective on the IMP innovation framework for policymakers and practitioners. Although this study presents a conceptual model of the IMP innovation island, further quantitative analysis is needed to strengthen the understanding of the effects of innovation islands on IMP innovation performance.

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