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Firm and project innovation outcome measures in infrastructure megaprojects: An interpretive structural modelling approach

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Abstracts

Infrastructure megaprojects are characterised by huge investment, vast complexity in technical and organisational terms, and extensive innovation. Innovation outcomes have been extensively investigated at the owner/operator and project-based firm/supplier levels (both combined shortly named 'firm-level'), with the project-level being far less studied and the simultaneously study of firm and project innovation being a knowledge gap. Considering the case of infrastructure megaprojects in China, this paper identifies infrastructure megaprojects' innovation outcome measures at both the firm-level and project-level simultaneously and investigates their relationships. This paper employs a mixed-method approach leveraging interpretive structural modelling (ISM) and the matrix of cross-impact multiplications analysis. The model derives 22 innovation outcome measures, divided into five hierarchy levels, describing owner-level, supplier-level, and project-level innovation in infrastructure megaprojects. Five measures have the greatest driving power: 1) Creation or improvement in construction technology, 2) Creation or improvement in the construction process, 3) Creation of new construction standards, 4) Creation or improvement of contract form, and 5) Creation or improvement in financial arrangements. The results can help researchers and practitioners better understand how to evaluate and manage innovations at both the firm-level and project-level in infrastructure megaprojects.

Keywords: infrastructure megaprojects, innovation outcomes, measures, relationships, project innovation.

Highlights:

- Infrastructure megaprojects are an ideal setting for innovation.
- Owner-level, supplier-level, and project-level innovation outcomes are simultaneously studied.
- We identified measures of innovation outcome at the firm-level and project-level and their relationships.
- Five innovation outcome measures have the greatest driving power.
- We identified counter-intuitive relationships that should be examined in further studies.

1. Introduction

Infrastructure megaprojects (hereafter referred to as ‘megaprojects’) are large-scale projects involving huge investments, extreme complexity and uncertainty, multiple stakeholders, providing essential public services for economic, social, and people’s lives (Davies et al., 2014; Locatelli et al., 2017). Innovation regarding megaprojects can help practitioners generate and develop new or significantly improved ideas for solving construction problems (Dodgson et al., 2015) or generating value (Stefan et al., 2021). Overall, innovation is fundamental in handling megaprojects’ uncertainty and complexity (Davies et al., 2017; He et al., 2019).

Megaprojects deliver unique products that can create a one-off opportunity to invest in basic or applied research and development, such as advanced construction technologies or unique construction processes (Gil et al., 2012; Sergeeva & Winch, 2020). For example, the Hong Kong-Zhuhai-Macao Bridge (HZMB) megaproject created a novel, world-class, immersed tube. Although innovations in projects and megaprojects are emerging topics, key elements still require investigation. It is unclear how practitioners and policymakers can determine whether innovation practices achieve the expected outcomes. To this end, Gambatese and Hallowell (2011) identified enablers and evaluation measures for managing innovation in the construction industry. Similarly, Ozorhon (2013) developed a model tailored for the project setting, including drivers, inputs, barriers, enablers, benefits, and impacts, to analyse the construction innovation process’s determinants and outcomes. Cantarelli (2020) suggested that, as an outcome, innovation in megaprojects included four dimensions: form, magnitude, referent, and type. The importance of measuring innovation outcomes in the infrastructure sector has attracted considerable attention (Panuwatwanich et al., 2008). Maghsoudi et al. (2016b) suggested that innovation in major infrastructure projects had been limitedly studied compared with other industries;

therefore, they investigated how innovation in major infrastructure projects in Australia was produced and captured. They concluded that few studies had built a framework to assess innovation outcomes, and evaluating innovation outcomes in major infrastructure projects was a practical and urgent need. However, measuring innovation outcomes is complex due to its uncertain nature and multifaceted process, particularly for megaprojects (Maghsoudi et al., 2016b). Therefore, instructive evaluation measures for measuring innovation outcomes in megaprojects should be developed.

To develop and present our research, we leverage the 'three domains of project organising' framework proposed by Winch (2014) which identifies the three key domains in project business. The first domain is 'Owners & Operators', for which projects are not the core business but rather are used to extend their core business infrastructure. An example is an electrical utility owning a portfolio of power plants and interested in building more (along with upgrading and eventually dismantling the existing plants). Owners & Operators provide the capital and are 'permanent organisations'. The second domain is 'Project-based firms', which can be specialist suppliers (e.g. first-tire contractors) working as system integrators. 'Owners & Operators' and 'Project-based firms' often have legal entities and, in the rest of the paper, when we generically refer to these organisations, we will use the term 'firm-level', while if refer to a specific one we will use 'Owner' or 'Supplier'. The last domain in Winch (2014)'s framework is called 'Projects and Programmes', which are the temporary organisations concerned with new product development or asset acquisition (e.g. the construction of a power plant). We use the expression 'project-level' to refer to projects and programmes.

Existing studies have investigated firm-level innovation outcomes in construction projects (Aouad et al., 2010), but only a few studies have explored project-level innovation. Ozorhon (2013) stated that construction innovation was co-developed at the project-level; however, most studies investigated innovation at the firm-level, and the project-level was overlooked. Fernando et al. (2020b) indicated that project-level innovation was under-researched as '*only 5 papers could be identified as discussing project-level innovation directly*' (p.730). Also, there remains a paucity of studies measuring innovation outcomes from both the project-level and firm-level simultaneously. From an enquiry on Scopus and Web of Science in May 2021 (Query: (TITLE-ABS-KEY ("Innovation outcome" OR "Innovation output" OR "Innovation performance" OR "Innovation evaluation") AND TITLE-ABS-KEY ("megaproject" OR "mega project" OR "large project" OR "major project") AND TITLE-ABS-KEY ("project-level") AND TITLE-ABS-KEY ("firm-level")), there is no article investigating innovation outcomes from both the project-level and firm-level in megaprojects. Also, innovation in megaprojects is usually co-developed by the two permanent organisations, including owners and suppliers (Winch, 2014), which simultaneously contributes to both firm-level and project-level innovation outcomes (Ozorhon et al., 2016). Innovation in megaprojects is process-based and organisation-based, which will facilitate the achievement of tangibles and intangibles outcomes at the firm-level and project-level simultaneously (Brockmann et al., 2016). Therefore, it is necessary to propose an integrative framework that combines firm-level and project-level innovation outcomes.

Innovation can be an evolutionary and interactive process promoted by interacting factors with dynamic features (Aouad et al., 2010). There are complex relationships among innovation outcomes in megaprojects (Cantarelli, 2020); however, general models of relationships among innovation outcomes remain unexplored. Therefore, this study primarily identifies megaprojects' innovation outcome measures for owners and first-tier suppliers (e.g. main contractors, consultants, designers, material suppliers) at both the firm-level and project-level simultaneously and investigates their relationships. First-tier suppliers are on the front line of reacting to innovation requirements from projects and owners

(Meng & Brown, 2018; Winch, 2001). From this background, we derived two research questions:

RQ1*: Which measures can describe megaproject innovation outcomes at the firm-level and project-level?*

RQ2*: What are the relationships between these measures?*

To address the research questions, first, this study reviews innovation outcomes at the firm-level and project-level to identify a set of measures for the owners and first-tier suppliers in megaprojects. Second, it adopts interpretive structural modelling (ISM) and the matrix of cross-impact multiplications analysis (MICMAC) to analyse the relationships among innovation outcomes. Therefore, the key novelty of this study is not in the identification of measures per se (even if it is a useful systematization of the literature) but in the identification of measures and their interrelationships describing megaproject innovation outcomes at the firm-level and project-level. The findings are significant to both academics and practitioners as they fill the gaps in evaluating innovation outcomes in megaprojects.

This study is structured as follows: Section 1 introduces the research background and questions. Section 2 presents the literature review. Section 3 discusses the research method. Section 4 discusses MICMAC analysis. Section 5 presents a discussion and suggestions for practitioners. Finally, Section 6 presents the conclusions.

2. Literature review

2.1 Megaprojects and innovation

Megaprojects are characterised by huge complexity, large-scale investment, complicated decision-making, long implementation cycles, and significant impacts on the economy, society, and environment

(Flyvbjerg, 2014; He et al., 2015; Locatelli et al., 2017; Wang et al., 2017; Zhang et al., 2021). There is an intrinsic complexity in megaprojects, which often induces alarming rates of failure. Chapman (2016) argued that six types of complexities — finance, context, management, site, task, and delivery complexity — posed threats to project performance in rail megaprojects. Kian Manesh Rad et al. (2017) regarded external complexity, comprising economy, environmental, legal and regulations, political, and social complexity, along with internal complexity, comprising organisation/team of delivery, the process of delivery, and project characteristics, as major contributors to project failure.

Innovation has been extensively investigated as a method for dealing with complexity and improving performance in construction projects (Slaughter, 1998); however, no universal definition of innovation exists. Brockmann et al. (2016) argued that innovation can be defined as changes resulting in an improved input-output ratio for products and processes within the technical, management, or legal organisations. In comparison, Chen et al. (2020) regarded innovation as '*the new practical application or technological knowledge applied in megaprojects that are different from prevailing practices*' (p.664). After reviewing studies, identifying the attributes of innovation, and testing with practitioners, Fernando et al. (2020b) presented project-level innovation as '*the application of ideas for new or improved products (including materials, plant, and equipment), software, technologies, methods, practices, and systems designed to benefit the project*' (p.3). Despite considerable efforts made by these studies, they have limitedly considered the special nature of infrastructure projects, especially the consideration of both project-level and firm-level innovation simultaneously. From Winch (1998)'s definition of innovation as '*management of new ideas into good currency*' (p.269), we define innovation in megaprojects as a novel or significantly improved ideas, products, processes, technologies, tools, and organisational methods at the project-level and firm-level, creating value for firms and megaprojects.

Based on the definition of Fernando et al. (2020b), project-level innovation is explained as new or improved products, project processes, construction technologies, methods, and systems adopted to achieve value for money. Firm-level innovation refers to novel or significantly improved ideas that are new to firms. Sometimes, firm-level innovation is created to meet the requirements of the project and owner's demand (Ozorhon, 2013).

There are different types of innovation in megaprojects, as suggested by Davies et al. (2019) and Slaughter (1998). Based on the magnitude of change from current practices and links to other components and systems, Slaughter (1998) constructed five models of construction innovation, which included incremental, modular, architectural, system, and radical innovation. These five types of innovation may occur in different project stages and require various resources and supervision. They also have different impacts and outcomes. Based on the knowledge-based view for successful innovation, two types of innovation were distinguished: explorative innovation and exploitative innovation (Lu & Sexton, 2006). Explorative innovation focused on owner-facing and project-specific problem solving, while exploitative innovation depended on '*internal organisation and general client development activity*' (Lu & Sexton, 2006, p. 1275). From Brockmann et al. (2016), product, technology, technical organisation, and management organisation innovation were typical innovations in megaprojects. Product innovation includes various categories, ranging from unique and customised productions to multiple and low standardisation productions (Davies et al., 2009). Technology innovation in megaprojects is implemented around engineering requirements specific to a certain project, such as D6 underslung girder and inclined elastomeric bearings in BangNa Expressway in Thailand (Brockmann et al., 2016). Technical organisations (e.g. contractors and designers) that arrange the integration and flow of technical components in the design or construction stage will contribute to technical organisation innovation (Brockmann et al., 2016). Leadership improvement and an efficient organisational culture are two examples of typical management organisational innovations (Fan et al., 2017). Other types of innovations, such as management (Davies et al., 2015), service (Roehrich et al., 2019), and financial innovation (Maghsoudi et al., 2016a), are also imperative in megaprojects. The identification of innovation types can provide a basis for innovation outcomes.

Different types of innovation initiatives, including both firm-level and project-level innovations in megaprojects, can facilitate different innovation outcomes, and different modes of innovation can have different impacts on innovation outcomes. However, extant studies do not indicate practical measures for innovation outcomes (Maghsoudi et al., 2016a). It is necessary to investigate innovation outcomes in megaprojects to provide valuable guidance. The next subsection describes the measurement and relationships of innovation outcomes.

2.2 Innovation outcomes

The innovation outcomes are different from innovation outputs that rely heavily on scientific and technological inputs and mainly promote the products and related production systems, such as publications and patents (Aouad et al., 2010). Innovation outcomes reflect the consequences of the introduction or implementation of innovations (Janger et al., 2017) and are regarded as important criteria for measuring innovation performance (Dziallas & Blind, 2019). Innovation outcomes comprise benefits and impacts (Ozorhon, 2013). Benefits are regarded as project-level outputs, while impacts are regarded as wider outputs resulting from the diffusion of innovation from the project onto the firm and industry (Ozorhon, 2013).

In infrastructural projects, studies have developed different measures for innovation outcomes at the firm-level. Ozorhon et al. (2016) showed that increased organisational effectiveness, experience acquisition, improvement of human resources, and better company image were positive innovation outcomes. From Fernando et al. (2020a), gaining competitive advantage, increased organisational commitment and higher organisational motivation, organisational effectiveness improvement, additional cost savings in future projects due to gained experience, enhanced corporate image and recognition, future collaboration along the supply chain, and knowledge transfer to inform future projects were all positive innovation benefits. Examples of positive innovation outcomes at the firm-level also include innovative products, patents, publications, customer experience improvement, knowledge transfer, and the firm’s competitiveness improvement (Su & Vanhaverbeke, 2019; Yaghmaie & Vanhaverbeke, 2020). However, the body of knowledge on measures for innovation outcomes concentrates mainly on small-or medium-sized infrastructure projects, which is not exactly transferable for measuring innovation outcomes in megaprojects. The measures from small-or medium-sized infrastructure projects cannot reflect the considerable impact of megaprojects on the society, economy, and people’s lives.

Though extant studies on innovation outcomes have mainly focused on firm-level analysis, a few recently published studies have begun to explore project-level innovation outcomes. Ozorhon and Oral (2017) assessed positive innovation outcomes at the project-level, including shorter project duration, decreased project cost, increased productivity, and increased client satisfaction. Noktehdan et al. (2019) proposed that direct cost saving or better utilisation of resources, reduction of lead-time or increasing speed for the project, improvement of quality, reducing adverse impact on communities affected by the construction project, reducing the adverse impact of the construction process, improving workers’ safety, health, and wellbeing were innovation benefits at the project-level. Fernando et al. (2020a) regarded decreased cost, client and end-user satisfaction improvement, and construction quality improvement as benefits at the project-level.

Although existing studies contribute to the investigation of innovation outcomes at the project-level, there are limited studies measuring innovation outcomes at the firm-level and project-level. This limitation was also confirmed by Maghsoudi et al. (2015), who aimed to develop a framework to evaluate firm-level and project-level innovation in infrastructure projects. The reason for evaluating innovation at the firm-level and project-level is that projects are temporary organisations created by permanent organisations (the firms delivering the projects) (Sergeeva & Winch, 2021). Innovation is usually conducted on the firm's projects rather than within the firm itself, as suggested by Winch (1998). Neither the practice nor the research on innovations is constrained at just the firm-level or project-level (West et al., 2006). The project-level and firm-level innovation outcomes coexist and are interrelated (West et al., 2006). It is imperative to analyse innovation outcomes at both the firm-level and project-level since neglecting either entity may impede full understanding of innovation management in megaprojects.

Extant studies have also investigated the relationships between innovation outcomes, especially the relationships among firm-level and project-level innovation outcomes; however, they have not reached a unified conclusion. Ozorhon et al. (2016) found that project-level innovation outcomes were connected with project performance (e.g. reduction in project duration and cost), while firm-level innovation outcomes were more extensive outputs (e.g. enhance corporate reputation), which may be affected by project-level outcomes. Maghsoudi et al. (2015) argued that innovation practices/activities initially achieved incremental innovation outcomes, and accumulation of these continuous incremental innovation outcomes may help achieve large positive impacts or even radical innovation outcomes on project outcomes. Furthermore, limited studies have explored the relationship among innovation outcomes in megaprojects. Overall, these findings are abstract and cannot provide valuable guidance for practitioners to manage innovation in megaprojects. Maghsoudi et al. (2016b) also confirmed that only a clear explanation of the relationships between innovation outcomes in the literature could be applied in practice.

3. Research method and model development

To evaluate innovation outcomes, a resource-based view (RBV) model is used. The RBV provides the theoretical lens through which explaining how competitive advantages and innovation outcomes are accomplished through firm resources and capabilities (Jin et al., 2019; Obradović et al., 2021). Based on RBV, successful innovation outcomes derive from *'a capability consisting of a bundle of resources controlled by the firm, and this ability to be innovative in product development will enable the firm to differentiate its products from those of its competitors and ultimately achieve superior overall performance'* (Andersén, 2021, p. 1). The core notions of the RBV are resources and capabilities. Resources can be regarded as a unique and valuable source of competitive advantage for firms and as '*stocks of available factors that are owned or controlled by the firm*' (Amit & Schoemaker, 1993, p. 35). Resources should be valuable, rare, inimitable, and non-substitutable (hereafter referred to as VRIN) (Barney, 1991), whereas capabilities reflect firms' ability to integrate resources (Grant, 1996). In megaprojects, firms use their valued resources and capabilities to conduct the innovation required and consequently help in achieving innovation outcomes (Greco et al., 2021). Therefore, the RBV can provide a valid theoretical perspective to investigate innovation in megaprojects by addressing the innovation outcomes at the project-level and firm-level.

Innovation outcome measures at the firm-level and project-level are dependent and have complex relationships (Ozorhon et al., 2016). This study leverages a mixed-method approach combining ISM and MICMAC to identify and analyse the relationships of innovation outcome measures in megaprojects. ISM has been extensively acknowledged as an appropriate qualitative method to decompose a complex system into several levels and construct a more explainable structured multilevel subsystem (Aloini et al., 2015), especially under the circumstance of *'a lack of supporting literature regarding exposing the relationship among critical factors'* (Kannusamy Panneer Selvam & Thangavelu, 2019, p. 609). This is ideal for this study as there are limited studies investigating innovation outcomes at the firm-level and project-level and their relationships regarding megaprojects. Compared with other methods (e.g. system dynamics and structural equation modelling), ISM and MICMAC can examine interaction and interrelationships, including both driving and dependence power/relationships (Bañuls et al., 2017). ISM is '*an interactive learning process in which a set of dissimilar and directly related elements are structured into a comprehensive systematic model*' (Mathiyazhagan et al., 2013, p. 285) and can identify hierarchical structures of complex relationships among all items (Aloini et al., 2015). The MICMAC analysis is used to expand impressions that researchers extract from a visual analysis of influence structures (Sagheer et al., 2009). Therefore, we adopt ISM and MICMAC to analyse the interrelationships among innovation outcome measures. The overall research design is shown in Fig. 1.

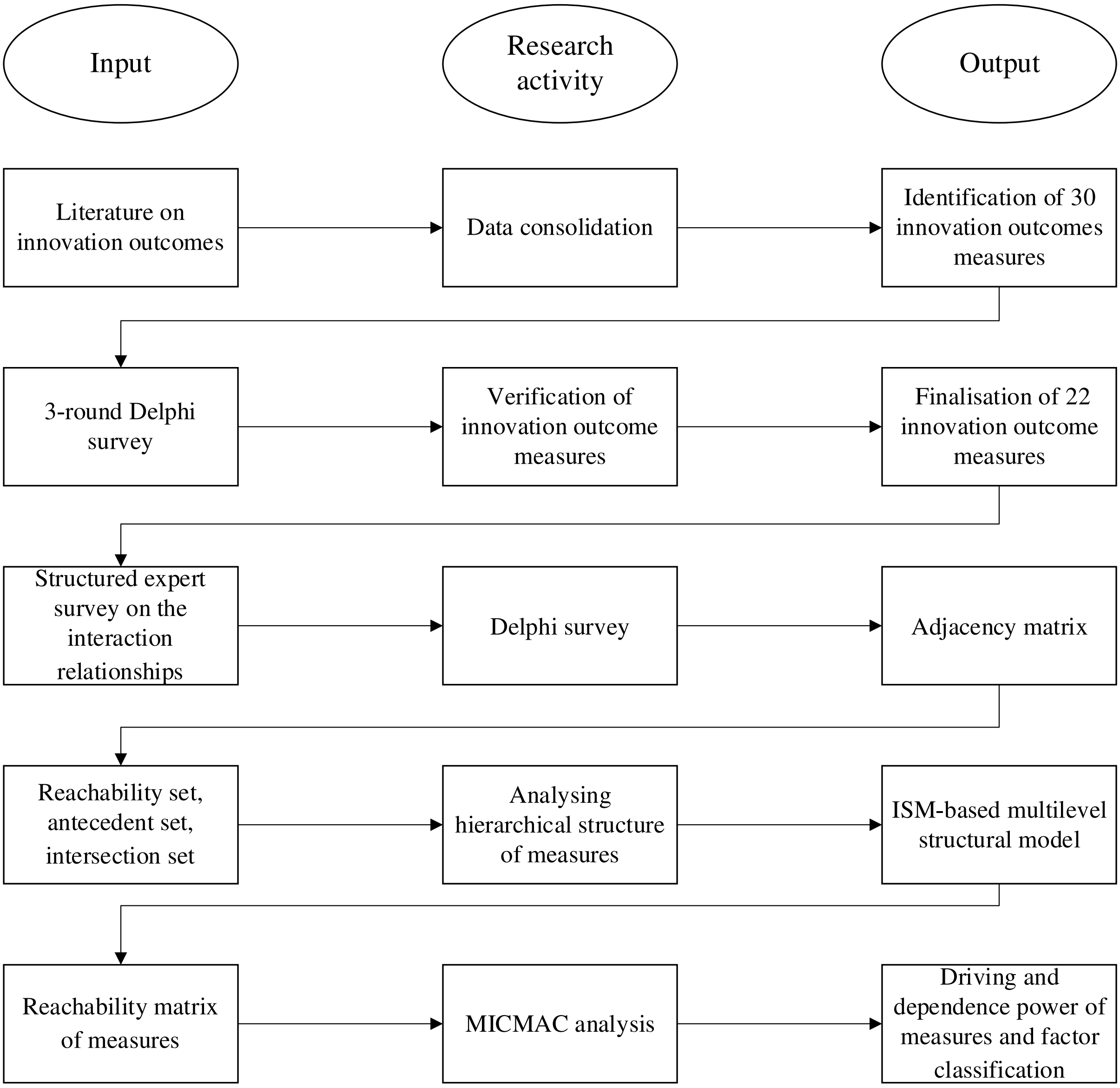

Fig. 1. Research design

From the literature, we identified 30 measures of innovation outcomes in megaprojects, which were reduced to 22 after a 3-round Delphi survey (Fig. 1). Subsequently, experts were invited to conduct pairwise comparisons to establish interrelationships. Furthermore, we developed the adjacency matrix and reachability matrix (R), conducted a level partition, and established an ISM-based model. MICMAC analysis was also implemented to determine the strength of the relationships among the measures. The following sections describe each step.

3.1 Identification and finalisation of measures

This study used data triangulation (literature review and Delphi surveys) to identify measures and improve validity and reliability. First, relevant studies published from 2010 to 2020 in peer-reviewed international journals indexed 'Web of Science' and 'Scopus' were scrutinised to provide a comprehensive set of potential innovation outcome measures. The search keywords are 'innovation evaluation' or 'innovation outcomes' or 'innovation outputs' or 'innovation performance' and 'major project" or 'mega project' or 'large project'. To ensure the quality of the literature review, only journal articles and reviews were considered. After reading the title and abstract, 21 studies were considered. From these studies, we derived 52 measures, along with a brief explanation to initially evaluate innovation outcomes. To reduce redundancy and duplication, the measures were re-arranged by comparing and merging when different measures were highly correlated and synonymous (e.g. time reduction and reduction in project duration). This re-analyse process reduced the number of measures from 52 to 30, and the remaining 30 measures are shown in Table 1.

<Insert Table 1>

Subsequently, the Delphi technique was adopted to evaluate the appropriateness of identified measures as it had been extensively accepted and applied in construction management studies (Manoliadis et al., 2006). The Delphi technique is a method requiring a panel of domain experts with abundant experience and knowledge (Han & Shin, 2014). Results of the Delphi technique are valid and reliable because they are experts' judgments in their specific domains (Manoliadis et al., 2006). Further, it is consolidated by repeatedly sending the same questionnaires to the experts (Abbassi et al., 2014). Although these collective judgments of experts comprise subjective opinions, they are more reliable than personal narratives (Mullen, 2003).

Questionnaire surveys were sent via email or instant messages to 54 experts in the first Delphi round. Also, they were structured in a two-page script (Appendix A). It included an introduction to the survey, basic information of experts, and judgment of the suitability of initial measures. The meaning of the 30 measures was also interpreted by the experts for better understanding. The suitability of initial measures was binarily measured (0-No, 1-Yes), aiming to evaluate whether such innovation measures are representative or not. The questionnaire survey was originally developed in English. Subsequently, the back-translation technique was adopted to translate it into Chinese (He et al., 2019). In the survey's first round, 25 experts received the invitation and sent his/her opinions to the researchers. From Rowe and Wright (1999) and Maheshwari et al. (2018), the number of experts in Delphi studies ranges from 3 to 30. Thus, the number of experts in this study is appropriate, and the key information related to those experts is summarised in Appendix B.

After receiving the first-round feedback, the researchers summarised the results of the experts' judgment. If, for a certain measure, the number of 'No' responses exceeded 80% of the total number of answers, the measure was deleted without further consideration, as suggested by Wang et al. (2019). Therefore, the first round of the Delphi analysis induced a reduction of the initial 30 measures to 24 measures. Based on the experts' judgment, six measures, namely, 'consistency with the neighbourhood', 'improvement in human resources', 'improvement of business structuring', 'achievement of established goals and objectives', 'enhancement of employee motivation', and 'identification of changes and new opportunities through the technology' were deleted.

For the second Delphi round, a questionnaire survey like the first round was sent to the 25 experts. In this round, the experts were required to reconsider whether they would change the first-round results and to further judge the innovation outcome measures. All the respondents completed the survey at the given time. After receiving the experts' second-round feedback, researchers analysed the results of their opinions and found that two measures, 'increased productivity' and 'service improvement', met the 80% in 'NO'; thus, the two measures were deleted.

To ensure the reliability and validity of the results, we conducted a third-round Delphi survey. A questionnaire like the second round was sent to the 25 experts again. In this round, all the experts reached a consensus, and no measures were deleted. Finally, 22 measures were adopted and coded to evaluate innovation outcomes (Table 1).

3.2 Pairwise comparison of identified measures

To conduct the pairwise comparison, we selected 10 leading experts (one owner, three contractors, three designers, two suppliers, and one researcher in a research institute) from the 25 megaprojects experts involved in the Delphi survey. There are three criteria for determining the sample size of experts. The first criterion is the number of experts involved. '*The number of qualified experts does not have to be big; for example, it can be as few as two experts*' (Shen et al., 2016, p. 216). The number of experts in this study, 10, is equal to or greater than Nilashi et al. (2019) and Prakash and Phadtare (2019). The second criterion is 'the heterogeneity of the population' and the quality of experts. We carefully sampled the experts according to three principles: (1) having more than five consecutive years working experience in megaprojects; (2) being among the following stakeholders in megaprojects: owner, contractor, designer, supplier, and researcher in research institute; (3) all being from different megaprojects, e.g. the HZMB megaproject, Beijing Daxing International Airport, etc. The third criterion is knowledge regarding our research scope: investigating innovation outcome measures and their relationships. Appendix B describes the sample of our experts.

These 10 experts were asked to perform a pairwise comparison between the innovation outcome measures through a structured survey. The first section of the survey stated the research objective and explained the meaning of each measure. Subsequently, experts were required to identify to what extent measure i led to measure j, which were measured by a 2-point scale (1-measure i has a direct influence on measure j, 0-measure i has no direct influence on measure j).

The Adjacency matrix (A) was created from the interaction relationships according to Formula (1) (Iyer & Sagheer, 2010). The *aij* is defined as 1 if measure *i* has a direct influence on measure *j*. Due to the discrepancies between experts' opinions, *aij* is set to 1 if no less than 80% of interviewees (which is more than seven interviewees in this study) agree that a direct relationship exists, as suggested by Chen and Wu (2010).

$$\text{aij} = \begin{cases} 1, if \;\; indicator \;\; i \;\; has \;\; a \;\; direct \;\; influence \;\; on \;\; indicator \;\; j \\ 0, \; otherwise \end{cases} \qquad (1)$$

Table 2 shows the Adjacency Matrix of innovation outcome measures in megaprojects.

<Insert Table 2>

The Reachability matrix (R) was developed from the adjacency matrix. The R can explain both the direct and indirect relationships between the innovation outcome measures. The primary hypothesis for interaction relationships in ISM is transitivity (Nandal et al., 2019). It means that if measure *i* leads to measure *j*, and measure *j* leads to measure k, it can be deduced that measure *i* leads to measure *j*. Based on the aforementioned hypothesis and the Boolean algebraic operation rule, R can be obtained using the following Formula (2)–(4):

$$A^r = (A+I)^r \tag{2}$$

$$A^1 \neq A^2 \neq A^3 \neq \dots A^{r-1} = A^r \tag{3}$$

$$R = A^{r-1} = A^r \tag{4}$$

Where I is the unit matrix, and r represents the number of iterations.

The reachability matrix of measures is obtained after 3-multiple iterations of (A + I) (as shown in Table 3).

<Insert Table 3>

3.3 Level partitioning of the final reachability matrix

To obtain the ISM-based model, the reachability matrix is partitioned and divided into reachability set (R(Ci)), antecedent set (A(Ci)), and intersection set (I(Ci)) according to principles (Table 4) (Iyer & Sagheer, 2010). The R(Ci), A(Ci), and I(Ci) for each innovation outcome measure can be found in the final reachability matrix. The R(Ci) comprises the measure itself and other measures that carry a value of 1 in the measure's row. For example, R(C1) comprises C1, C8, C9, C19, C21, and C22, as can be identified from the value 1 in the row corresponding to C1. The A(Ci) comprises the measure itself and other measures having a value of 1 in the column of that measure. For example, A(C4) comprises C4, C8, and C12, as can be identified from the value 1 in the column corresponding to C4. The I(Ci) is derived from all intersecting measures between the reachability and antecedent set (Iyer & Sagheer, 2010).

<Insert Table 4>

For any measure *i*, based on ISM methodology, if R(Ci) is a complete subset of A(Ci), measure *i* will be extracted and arranged at a particular level (Iyer & Sagheer, 2010). In this study, the R(Ci) of measures C8, C9, C19, C21, and C22 is a complete subset of A(Ci) (Table 4). Thus, measures C8, C9, C19, C21, and C22 are extracted from the R(Ci) and defined in hierarchy Level I. Subsequently, for the remaining measures, the same method was used to identify measures in different levels. The repetition of the same exercise was conducted until all measures were exhausted, and each hierarchical level for the measures was identified (Table 4). Finally, the 22 measures were divided into five levels.

3.4 ISM-based multilevel structural model

The ISM-based multilevel model (Fig. 2) stems from the hierarchy level identified in Table 4 and the final reachability matrix in Table 3. The model includes nodes and direct arrows, where nodes denote measures and direct arrows denote the direct interrelationships between two measures. For example, a direct relationship exists between measure C1 and measure C8; thus, a direct arrow pointing from C1 to C8 presents it. Level I is located at the top of the hierarchy. Level II is located in the second hierarchy and is placed just below Level I. Level III is underneath Level II. This process is repeated until each hierarchical level is set.

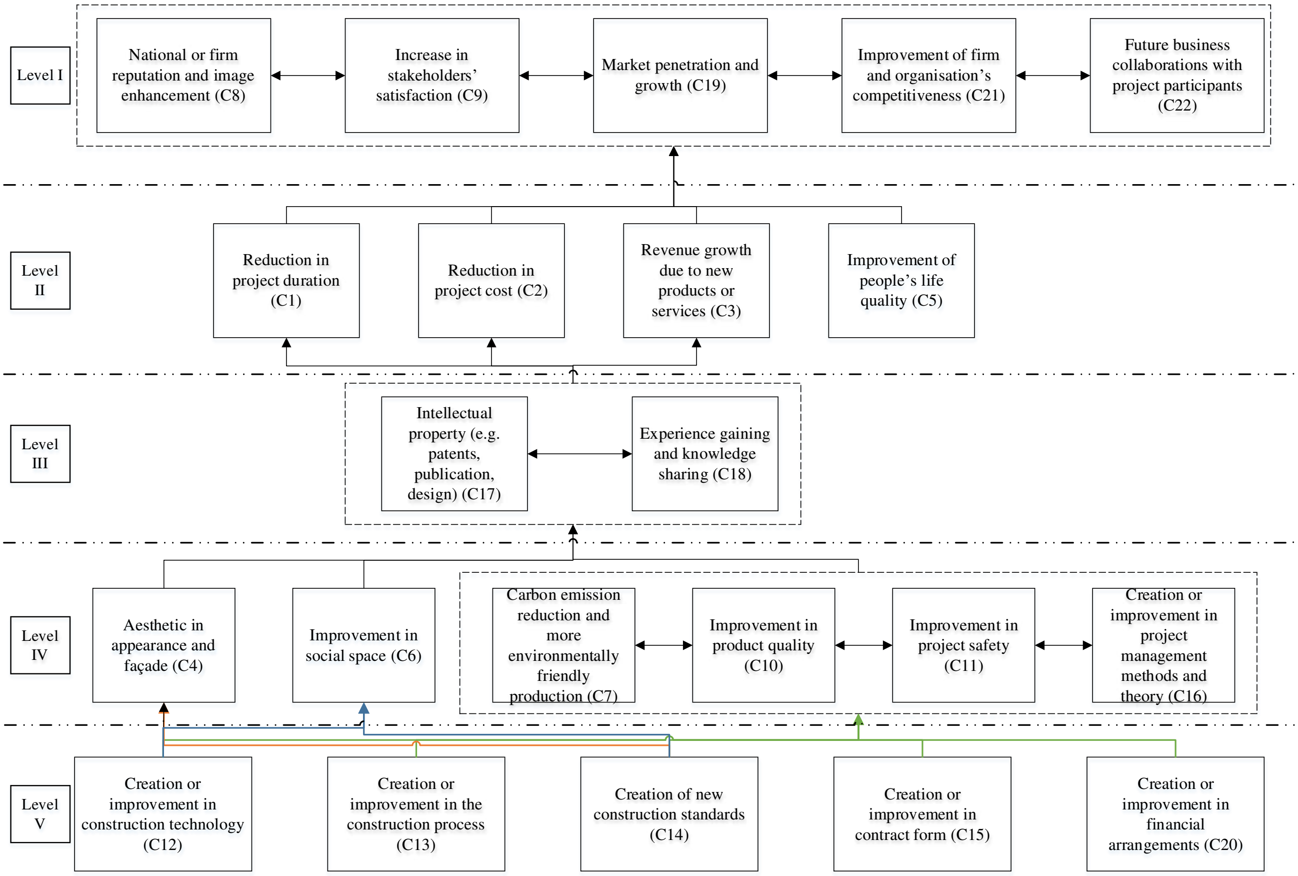

Fig. 2. ISM-based model of measures for innovation outcomes

The ISM-based model shows that a group of measures—'National or firm reputation and image enhancement (C8)', 'Increase in stakeholders' satisfaction (C9)', 'Market penetration and growth (C19)', 'Improvement of firm and organisation's competitiveness (C21)', and 'Future business collaborations with project participants (C22)'—are identified as the top-level innovation outcomes (Level I). These measures are highly dependent on other measures and cannot drive any other measures in the model.

In contrast, a group of measures—'Creation or improvement in construction technology (C12)', 'Creation or improvement in the construction process (C13)', 'Creation of new construction standards (C14)', 'Creation or improvement in contract form (C15)', and 'Creation or improvement in financial arrangements (C20)'—are located at the bottom of the model (Level V) and serve as the foundation of the ISM-based model, which means that they have a strong driver to influence other innovation outcomes above Level V to achieve more innovation outcomes and do not depend on other measures.

To make it easy to understand, we define Level I as ‘long-term benefit’, Level II as ‘project performance’, Level III as ‘intellectual capital’, Level IV as ‘product performance’, and Level V as ‘innovation management’.

4. MICMAC analysis for innovation outcomes

Combined with the ISM-based model, the MICMAC analysis was further adapted to determine the strength of the relationships among the measures. Driving and dependence power were two significant parameters for MICMAC analysis. The driving power of different measures is the summation of 1s in the row that it affects on, while the dependence power of separate measure is the summation of 1s in the column that it is affected (Sarhan et al., 2019). For example, the driving power of C1 is the sum of six measures, including C1, C8, C9, C19, C21, and C22, that are affected by C1. Similarly, the dependence power of C1 is the sum of 14 measures, including C1, C4, C6, C7, C10, C11, C12, C13, C14, C15, C16, C17, C18, and C20, that influence C1. Based on driving and dependence power, as shown in Table 3, all measures are plotted into a digraph of four quadrants: autonomous, linkage, dependent, and independent (Iyer & Sagheer, 2010) (Fig. 3).

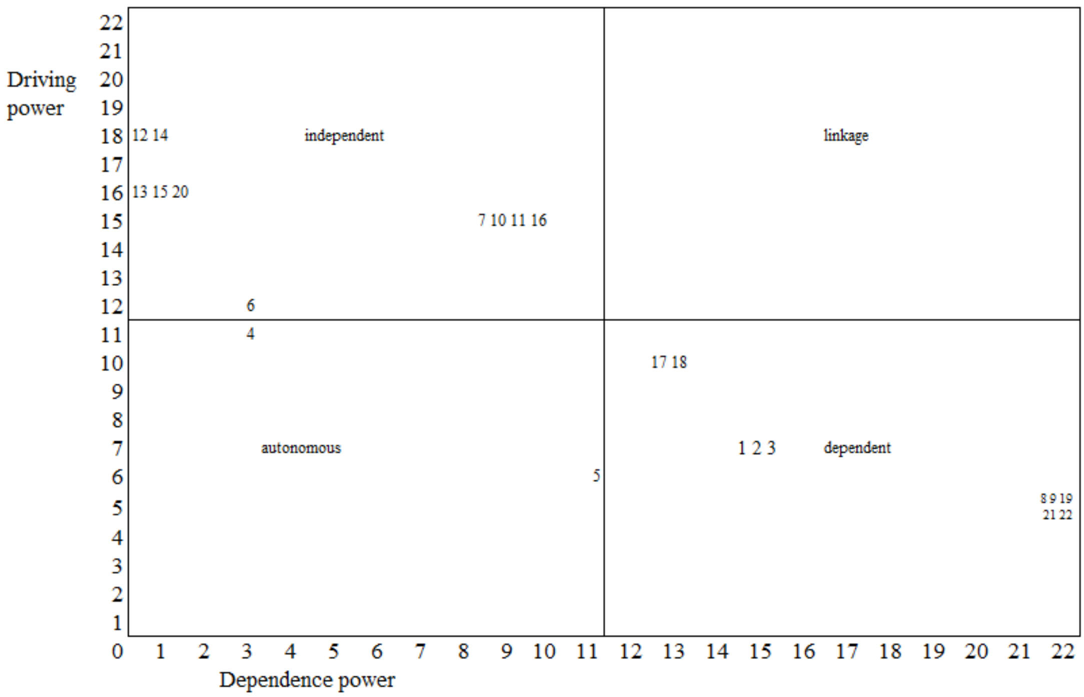

Fig. 3. Driving power and dependence power of measures for innovation outcomes

The autonomous quadrant comprises measures with relatively weak driving and dependence power. The autonomous quadrant is regarded as a relatively disconnected measure, which means that these measures do not disturb the system and are not influenced by the system. In this study, only two measures (C4 and C5) belong to the autonomous quadrant. The driving power of C4 is 11, which is close to the dividing line, and the dependence power of C5 is 11, which is also close to the dividing line. No more modifications are needed, and the results are acceptable, according to Maheshwari et al. (2018). The results indicate that all the measures in this study are significant for evaluating innovation outcomes and are closely interconnected in the ISM model.

The innovation outcomes independent quadrant has weak driving power but strong dependence power. In this study, there were 10 measures in the dependent quadrant. ‘National or firm reputation and image enhancement (C8)’, ‘Increase in stakeholders’ satisfaction (C9)’, ‘Market penetration and growth (C19)’, ‘Improvement of firm and organisation’s competitiveness (C21)’, and ‘Future business collaborations with project participants (C22)' are highly dependent on other innovation outcomes with a dependence power of 22, which is why they are located at the uppermost (Level I) of the ISM-based model (Fig. 2). 'Reduction in project duration (C1)', 'Reduction in project cost (C2)', 'Revenue growth due to new products or services (C3)', 'Intellectual property (e.g. patents, publication, design) (C17)', and 'Experience gaining and knowledge sharing (C18)' appear at Level II and Level III and drive Level I considerably. These measures contain the firm-level and project-level innovation outcomes and have a deep influence on innovation performance and construction firm performance.

The linkage quadrant includes measures with strong driving and dependence power. Measures in the linkage quadrant can affect other measures, and they are also dependent on other measures. Thus, measures in this quadrant are unstable, and changes occurring in them will affect other measures and may create a feedback loop (Maheshwari et al., 2018). In this study, none of the 22 measures belonged to the linkage quadrant. The results indicate that all measures are reliable and stable.

The independent quadrant comprises measures with strong driving power but weak dependence power. There are 10 measures in this quadrant. Most of these measures are located at the bottom of the ISM-based model, including Levels IV and V (Fig. 2). Also, nine measures have a driving power of 15 or more. These measures have great driving power on the system and serve as the root source of innovation outcomes in megaprojects. For example, the creation or improvement in construction technology conducted by suppliers has a deep influence on intermediate innovation outcomes and top-level innovation outcomes.

5. Discussions and implications

Often, the main purpose of innovation in megaprojects is improving project performance. However, having a purpose and achieving it are different things; therefore, the interplay between innovation outcomes and project performance is often complex and unclear. Practitioners need to know whether their innovative activities have achieved expected outcomes. Effective measures for innovation outcomes are therefore critical in evaluating the actual outcomes (Maghsoudi et al., 2016a). Extant studies have mainly focused on firm-level innovation outcome measures, with the project-level being limitedly explored (Fernando et al., 2020a). The combined study of both firm-level and project-level innovation outcomes is a relevant knowledge gap. This study aims to identify megaprojects' innovation outcome measures for owners and first-tier suppliers (e.g. main contractors, consultants, designers) at both firm-level and project-level simultaneously and investigate their relationships. An ISM-based multilevel model was developed to investigate relationships and hierarchical structures of measures. Figs. 2 and 3 summarise the key results. This section discusses the research findings and their implications for both theory and practice.

This study contributes to knowledge by identifying megaprojects' innovation outcome measures for owners and first-tier suppliers (e.g. main contractors, consultants) simultaneously at both firm-level and project-level. Of all 22 measures, seven measures are firm-level innovation outcomes, including 'Revenue growth due to new products or services (C3)', 'National or firm reputation and image enhancement (C8)', 'Intellectual property (e.g. patents, publication, design) (C17)', 'Experience gaining and knowledge sharing (C18)', 'Market penetration and growth (C19)', 'Improvement of firm and organisation's competitiveness (C21)', 'Future business collaborations with project participants (C22)', and 15 remaining measures are project-level innovation outcomes.

Some measures (e.g. ‘Increase in stakeholders’ satisfaction (C9)’ and ‘National or firm reputation and image enhancement (C8)’) are similar to Ozorhon et al. (2016). They showed that innovation benefits include productivity improvement and client satisfaction at the project-level and improvement of the firm image, technical, and managerial capability at the firm-level. Similarly, Maghsoudi et al. (2016a) divided innovation outcomes of building projects into six groups, including economic, quality, social, environmental, satisfaction, and soft and organisational impacts. However, a few innovation outcome measures, including ‘innovation management’ (a group of measures C12, C13, C14, C15, C20 in Level V), are different from the existing studies and are selected for their prominence in innovation in megaprojects. Compared to regular projects, megaprojects are more complex and uncertain; traditional innovations may not meet construction requirements, and new ideas and resources are often required (Davies et al., 2014).

Another novelty of this study is considering innovation measures relevant for society and the environment: ‘Improvement of people’s life quality (C5)’, ‘Improvement in social space (C6)’, ‘Carbon emission reduction and more environmentally friendly production (C7)’, and ‘National or firm reputation and image enhancement (C8)’. Traditionally economic outcomes (e.g. reduction in project cost) are regarded as the only value-creation for innovation (Maghsoudi et al., 2016b), but innovation is a key determinant for social/environmental outcomes that are imperative in measuring innovation outcomes.

5.1 Relationships among innovation outcomes

Relationships among innovation outcome measures are investigated following the suggestion for future study suggested by Ozorhon and Oral (2017). The ISM-based multilevel model (Fig. 2) shows that project-level and firm-level innovation outcomes have interrelationships. For example, ‘long-term benefit’ (a group of measures ‘National or firm reputation and image enhancement (C8)’, ‘Increase in stakeholders’ satisfaction (C9)’, ‘Market penetration and growth (C19)’, ‘Improvement of firm and organisation’s competitiveness (C21)’, and ‘Future business collaborations with project participants (C22)’ in Level I) contain both firm-level and project-level innovation outcome measures and are supported by project-level and firm-level ‘project performance’ (a group of measures ‘Reduction in project duration (C1)’, ‘Reduction in project cost (C2)’, ‘Revenue growth due to new products or services (C3)’ and ‘Improvement of people’s life quality (C5)’ in Level II). However, the aforementioned results differ from existing studies. Ozorhon et al. (2016) showed that project-level innovation outcomes had a significantly positive effect on firm-level innovation outcomes in construction projects. They also indicated that project-level innovation outcomes enhance firm performance. The difference may stem from different study contexts (ordinary construction projects VS megaprojects). Compared with ordinary projects, megaprojects are more complex and uncertain; firms need to make changes and improvements in technology or management to address new and unique challenges (Brockmann et al., 2016). These innovation initiatives at the firm-level may contribute to improving project quality and creating new construction methods, which will further help suppliers or owners gain valuable knowledge and improve competitiveness.

The driving and dependence power (Fig. 3), along with the hierarchy structure of the ISM-based model (Fig. 2), show detailed interrelationships among innovation outcome measures. From Figs. 2 and 3, it is clear that ‘innovation management’ (a group of measures C12, C13, C14, C15, and C20 in Level V) has the highest driving power and emerges as the root contributions to other innovation outcomes. This means that if ‘innovation management’ (a group of measures C12, C13, C14, C15, and C20 in

Level V) activities do not meet requirements in practice, there is a high chance that the achievement of innovation outcomes at higher levels may cause a discount. The finding is consistent with Brockmann et al. (2016), who argued that continuous incremental improvements made by both owners and suppliers were crucial in contributing to significant changes in megaprojects. Also, ‘innovation management’ (a group of measures C12, C13, C14, C15, and C20 in Level V) contributes to ‘project quality’ (a group of measures C7, C10, C11, and C16 in Level IV). The finding corresponds with Bynum et al. (2013), which regarded the suppliers’ capability to adopt innovative technologies or processes, for example, building information modelling (BIM), as means of increasing total project quality. This is because new technologies which are created by suppliers of project-related services possess some advantages, such as promoting project coordination and visualisation (Bynum et al., 2013), reducing carbon emissions (Liu et al., 2019), and reducing casualties (Chen et al., 2018). Owners and first-tier suppliers’ ‘innovation management’ (e.g. early contractor involvement, improved Design-Build contract, improvement in contract form between owners and suppliers) can also improve the quality of project management, relationships between owners and suppliers, quality of construction projects, and ability to accelerate schedule (Eadie & Graham, 2014; Sun & Zhang, 2011; Wang et al., 2013; Wang et al., 2016). However, the implementation of innovation management could also induce poor product performance or even failures (Yu et al., 2020), especially regarding megaprojects, where ‘*innovations often involve high levels of risk and uncertainty, making the project more complex*’ (Cantarelli, 2020, p. 12). Some ‘innovation management’ practices can even induce the adoption of other innovations as the implementation of one certain innovation needs various resources and firms’ capabilities; thus, the adoption of a unique ‘innovation management’ may cause more complexity and uncertainty in innovation (Cantarelli, 2020).

Besides, ‘Creation or improvement in construction technology (C12)’ and ‘Creation of new construction standards (C14)’ in Level V induce the achievement of ‘Aesthetic in appearance and facade (C4)’ and ‘Improvement in social space (C6)’ in Level IV. The finding corresponds with Ahmad and Thaheem (2017), Hu et al. (2019), and Alshamrani et al. (2014), which demonstrated that the latest technologies and improved construction standards (e.g. 4D BIM, LEED) conducted by suppliers could improve the social sustainability and appearance of buildings. Advanced technologies and improved construction standards are imperative for improving human’s living environment and aesthetics and layouts of construction projects (Chen & Shih, 2009; Leonard et al., 2019), as they could integrate visualisation, simulation, and dynamic analysis into the design process or even the whole lifecycle (Fanning et al., 2015; Leonard et al., 2019).

‘Product performance’ (a group of measures C4, C6, C7, C10, C11, and C16 in Level IV) has a positive effect on ‘intellectual capital’ (a group of measures C17 and C18 in Level III). This result is counter-intuitive and opposes previous studies. Chen et al. (2014) indicated that intellectual capital was a treasured resource for firms to improve product performance based on the knowledge-based view. Chai et al. (2011) also concluded that intellectual capital was crucial in accumulating and exploiting heterogeneous knowledge resources and ultimately promoting new product performance. The reason for the difference may be derived from the high requirements of innovation in megaprojects, where the choice to adopt innovations is ‘*a direct result of the technical complexity of the project, and particularly the lack of experience with the new technologies, methods, and delivery methods*’ (Cantarelli, 2020, p. 7). Usually, common innovations cannot be applied directly to megaprojects, and both owners and suppliers need to conduct explorative innovation to entail search, variation, experimentation, and activity to search for valuable knowledge and resources and solve project-specific problems (Lu &

Sexton, 2006; Ryan et al., 2018). The intellectual capital and experiences were accumulated when owners and suppliers have to achieve high 'project quality' (a group of measures C7, C10, C11, and C16 in Level IV) and social sustainability. This process has been verified by many megaprojects; for example, the measures and experiences of protecting Sousa Chinensis in Hong Kong-Zhuhai-Macao Bridge have been summarised by owners and suppliers for future megaprojects, especially for cross-sea bridges or tunnels (LIU et al., 2018).

'Intellectual capital' (a group of measures C17 and C18 in Level III) contributes to the improvement of 'project performance' (a group of measures C1, C2, C3, and C5 in Level II). Previous studies confirm that intellectual capital increases project performance due to the value achieved from knowledge assets (Handzic et al., 2016) and acts as a critical success factor to promote project success (Bayiley & Teklu, 2016). Intellectual capital contains three components: human, relational, and structural capital (Sveiby, 1997). Human capital refers to project teams that are included in the project and contain project managers and team members. The project teams or suppliers are responsible for integrating various resources (e.g. human resources, material resources, knowledge, etc.) and taking innovative measures when necessary to improve project performance (Handzic et al., 2016). The suppliers also need to '*give attention to the renewal of those resources through training and innovation respectively*' (Winch, 2014, p. 727) to promote the successful delivery of the project. Relational capital is defined as an interaction with project stakeholders who call for the project and obtain profits or suffer losses from project outcomes (Handzic et al., 2016). The suppliers' capability to maintain credible relationships (e.g. collaborative innovation relationships, partnerships) with both internal and external stakeholders using state-of-the-art methods promotes project implementation and contributes to the improvement of project performance (Sainati et al., 2017; Zhao et al., 2018). Also, suppliers have to pay attention to their relationships with owners who work as a purchaser and strategic actor (Winch, 2014) to achieve expected project performance and even promote future collaborations. Structural capital, which describes the technical infrastructure, organisation structure, databases, R&D, the organisational culture of suppliers, etc., is an important input to project success (Łataś & Walasek, 2016).

We also find that 'project performance' (a group of measures C1, C2, C3, and C5 in Level II) induces an increased 'long-term benefit' (a group of measures C8, C9, C19, C21, and C22 in Level I). The phenomenon is often described in new product development literature, where high project performance induces satisfactory market performance (Mishra & Shah, 2009). The explanation is that suppliers' superior project performance regarding its features and innovativeness has been regarded as a significant factor in differentiating new project/product winners from losers (Mishra & Shah, 2009). Due to the complexity of megaprojects, suppliers need to conduct many innovations to solve project-specific problems, which can achieve high project performance in the short term, improve suppliers' competitive advantage, promote future collaboration.

5.2 Theoretical implications for future research

This study pioneers the research stream aimed to identify innovation outcomes at the firm-level and project-level and test the identified relationships, particularly those presented in Fig. 2. The innovation outcomes are achieved by a configuration of project organisations (e.g. owners, suppliers, and the nature of megaprojects) that gather to set up a temporary coalition (Winch, 2014). Owners and suppliers make different contributions to innovations and gain different outcomes and benefits; thus, how to handle the distribution of innovation effort and outcomes across them is a new and challenging research agenda. We propose to investigate the distribution of innovation effort and outcomes based on the ‘three domains of project organising’ framework proposed by Winch (2014).

Each arrow in Fig. 2 shows the hypothesis of a relationship that should be tested in a more extensive study. Following an internal sense-making of the results, we suggested the test of the following hypothesis as particularly significant.

HP 1 - Improving the ‘project quality’ (a group of measures C7, C10, C11, and C16 in Level IV) induced an increase in the ‘intellectual capital’ in the firm (a group of measures C17and C18 in Level III).

Interestingly, since established knowledge (e.g. (Bayiley & Teklu, 2016); Hsu et al. (2014); Negash and Hassan (2020)) showed that intellectual capital drives project quality, we suggest testing the vice versa in the context of megaprojects.

HP2 - Innovation on the governance (a group of measures C15 and C20 in Level V) directly induces improvement in the project quality (a group of measures C7, C10, C11, and C16 in Level IV).

Governance innovation is risky and could induce both positive and negative outcomes. Himmel and Siemiatycki (2017) indicated that ‘*innovations that lower cost, such as shrinking the building footprint may technically meet the performance specifications but can leave service providers or users worse off*’ (p.761). Also, the vast (often controversial) literature on public-private partnerships reflects this (Eaton et al., 2006; Kivilä et al., 2017; Osei-Kyei & Chan, 2015; Roumboutsos & Saussier, 2014). Therefore, the extent and limit of these relationships should be carefully tested in different contexts.

HP3 – All three components of intellectual capability (human, relational, and structural capital) can improve ‘project performance’ (a group of measures C1, C2, C3, and C5 in Level II).

Extant studies have investigated the positive effect of intellectual capital on project performance in different project contexts, such as information technology (Handzic et al., 2016), international development (Bayiley & Teklu, 2016), and traditional construction projects (Negash & Hassan, 2020). However, limited knowledge exists on how the three components of intellectual capability (human, relational, and structural capital) interact with each other and interfere with project performance regarding megaprojects.

5.3 Managerial implications

This study's findings have four crucial managerial implications. First, practitioners need to pay more attention to 'innovation management' (a group of measures C12, C13, C14, C15, and C20 in Level V) in megaprojects. These innovations have the highest driving power and can induce the adoption of other innovations, which may lead to both positive and negative outcomes (Cantarelli, 2020). Therefore, suppliers need to collaborate with enterprises in other industries (e.g. the manufacturing sector) to achieve smart construction (Greco et al., 2021). These collaborations can contribute to new or improved products, technologies, and processes, foster the development of a functional network, and even gain more superior resources to enable their competitiveness in the long term (Yaghmaie et al., 2020). Owners who play a key role in innovation (Brandon & Lu, 2009) should review their commercial relationship with suppliers, such as the financial and contract arrangement, to achieve mutual success.

Second, owners should consider innovation outcome measures outside the traditional iron triangle of projects (time, cost, scope) and pay attention to the challenges of innovation and project management (Winch & Cha, 2020). More consideration should be given to measures—'Aesthetic in appearance and facade (C4)', 'Improvement in social space (C6)', 'Carbon emission reduction and more environmentally friendly production (C7)', 'Improvement in project safety (C11)', and 'Intellectual property (C17)'. Suppliers need to focus more on long-term benefits, such as 'Creation or improvement in project management methods and theory (C16)’, ‘Intellectual property (e.g. patents, publication, design) (C17)’, ‘Experience gaining and knowledge sharing (C18)’, and ‘Future business collaborations with project participants (C22)’. These measures are the building block of a new management philosophy in megaprojects shifting from the narrow, short-term success of the iron triangle to the long-term holistic success of contributing to sustainable development and achieving the UN sustainable development goals (Wang et al., 2020).

Third, both owners and suppliers need to recognise that innovation in megaprojects is accumulated and systemic, as shown in Fig. 2, which shows the hierarchy structure of innovation outcomes. Technology, process, construction standard, contract form, and financial arrangement innovation are the key determinants in megaprojects. However, these innovations cannot and should not be pursued independently, but only as an organic system aimed to innovate in specific megaprojects. Achieving these innovations is not only relevant at the project-level but can also induce firms’ benefits, such as enhanced reputation.

Fourth, owners and suppliers need to pay more attention to the interfaces between the three domains of project organisations and the dynamic changes through the lifecycle. Forming an appropriate relationship governance plan (e.g. choosing suitable innovation brokers) (Winch, 2019; Winch & Courtney, 2007) for the lifecycle and changing them if necessary, are appropriate methods to promote innovation and share innovation outcomes.

6. Conclusions

Although innovation outcomes have been extensively studied at the firm-level, there is a dearth of studies simultaneously analysing both project-level and firm-level innovation outcomes. This novel study is ambitious and innovative based on a limited sample in which measures and their hypothesised relationships are clarified in preparation for a suite of other full-scale quantitative studies.

This study provides three main contributions. First, this qualitative study generates hierarchy relationships between different innovation outcomes, which can be used in quantitative research that studies the direct or indirect effects among the different levels of innovation outcomes. Second, having reliable and robust innovation outcome measures at the firm-level and project-level can provide practitioners, especially owners, with a benchmark to evaluate innovation outcomes. Third, it can assist practitioners in better understanding the relationships between different innovation outcomes and making appropriate innovation decisions to manage innovation activities and improve project performance.

This study's findings show that, in the context of megaprojects, there are 15 project-level innovation outcome measures and seven firm-level innovation outcome measures that can be divided into five levels. The 22 measures have complex interrelationships, where Level V-'innovation management' (a group of measures C12, C13, C14, C15, and C20 in Level V) has the greatest driving power and contributes to the accumulation of continuous innovation outcomes at both the firm-level and project-level. All measures below Level I-'long-term benefit' (a group of measures C8, C9, C19, C21, and C22 in Level I) contribute to its achievement. We also identified counter-intuitive relationships that should be examined in further studies.

The findings support megaproject managers with an efficient and effective list of measures to evaluate innovation in megaprojects and help them understand the interrelationships of innovation outcomes enabling effective measures in managing innovation in megaprojects. The measures suggested in this study can contribute to innovation outcomes and their management in practice for megaprojects. This study provides practitioners, especially project owners who act as innovation champions (Sergeeva & Zanello, 2018), with key measures to determine the efficiency of the innovation initiatives implemented in the projects.

This study has three limitations. The first limitation is geographical because it is based on megaprojects and surveys in China mainland. Future research can replicate this study in other contexts (e.g. developed countries, Global South) since innovation in megaprojects in different contexts is likely to be managed differently (Bagherzadeh et al., 2021). The second limitation is methodological since the hierarchical structures can present the qualitative interrelationships between innovation outcomes, but it cannot quantify the size of the impact. Future studies could conduct a quantitative analysis to show the impact. The third limitation is that this study focuses on owners and first-tier suppliers in megaprojects. Future studies can improve this by investigating both first-tier suppliers and second-tier suppliers and making comparisons.

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Appendix A

Sample of the Questionnaire

Dear Sir/Madam,

This questionnaire survey aims to identify measures of megaprojects innovation outcomes. Megaprojects are large-scale projects involving large investments, extreme complexity and uncertainty, multiple stakeholders, providing fundamental public services for economic, social, and people's life. Measures of megaprojects innovation outcomes are used to evaluate the innovation outcomes.

The below questions focus on selecting suitable measures for innovation outcomes. Please answer the questions based on your innovation experience in a specific project.

1. Your gender

A. Male B. Female

2. What is the age of your company? ______

3. How many years have you been working in megaprojects?

A. 1-5 years B. 5-10 years C. more than 10 years

4. What kind of stakeholder are you in megaprojects?

A. Clients B. Consultants C. Universities D. Research institutes E. Contractors F. Suppliers G Designers H others,______

5. What is your position in your company?

A. Project manager B. Site Chief C. Site Engineer D. Architect E. Planning and Cost Control Manager F. Business Development Manager

6. What type of megaprojects do you engage in?

A. Infrastructure B. Transportation C. Energy D. Large-scale signature architecture and cultural megaprojects E. Others,______

7. Please indicate to whether the below listed measures can be used to measure innovation outcomes in megaprojects?

Innovation outcome measures	Description	Suitability (0-No, 1-Yes)
Reduction in project duration	Completing the megaprojects ahead of schedule	
Reduction in project cost	Reducing the costs used in completing the megaprojects	
Revenue growth due to new products or services	New products or services can help firms to gain more monetary income	
Aesthetic in appearance and façade	Making buildings more beautiful and good-looking	
Increased productivity	Innovations can help increase production efficiency	
Consistency with the neighbourhood	Be in harmony with the neighbourhood and respect their opinions and local custom	
Improvement of people's life quality	New/improved products can change the lifestyle of people and improve people's lives	
Improvement in social space	Increasing public space, green space, et al	
Carbon emission reduction and more environmentally friendly production	By adopting new production methods to reduce carbon emissions and achieve environmentally friendly production	
Service improvement	Creating new methods and adopting new visions can enhance service performance	
National or firm reputation and image enhancement	Creating world-class technologies can help improve national or firm's reputation and image	
Increase in stakeholders' satisfaction	By controlling and managing influence factor on innovation to achieve expected goals and increase participants' satisfaction	
Improvement in product quality	Innovation can improve the deficiencies of existing products and improve product quality	
Improvement in project safety	By creating new construction techniques or methods to improve the construction workers and buildings' safety	
Creation or improvement in construction technology	Creating or improving technologies related to project implementation, e.g. prefabricated technology	
Creation or improvement in the construction process	Creating or improving process related to planning or delivering projects, e.g. the contractor selection process, payment process, bidding, and tendering process, etc.	
Creation of new construction standards	Establishing or improving standards for buildings' quality, safety, etc.	
Creation or improvement in contract form	Making changes to the deficiency in the existing contract form or creating a new contract to meet megaprojects' specific requirements	
Creation or improvement in project management methods and theory	Creating or improving the discipline of project planning, organising, managing, e.g. adopting agile/lean construction	
Intellectual property (e.g. patents, publication, design)	Gaining patent authorisation for the creation or publishing of new books on the megaprojects to make more money	
Experience gaining and knowledge sharing	Experience and knowledge gained by a firm can be used in future megaprojects and shared among participants	
Market penetration and growth	Helping firms to gain more market share	
Creation or improvement in financial arrangements	Creating or improving financial method for the megaproject, e.g. debt, private money, equity	
Improvement in human resources	Improving the mechanism for recruiting and training talents	
Improvement of business structuring	Improving the business methods used in the megaproject, e.g. option development, improving project initiation	
Improvement of firm and organisation's competitiveness	Help firms master the core technology or knowledge to rival competitors	
Achievement of established goals and objectives	Finishing megaprojects' goals or specific goals set by the client	
Future business collaborations with project participants	Developing good relationships with other participants and forming a consortium to bid	
Enhancement of employee motivation	Motivating employee to participate in innovation activities	
Identification of changes and new opportunities through the technology	Technology innovation can bring some opportunities, e.g. accessing overseas market	

Appendix B

Profiles of 25 megaprojects professionals

Expert	ISM	Years of experience	Stakeholder role	Megaproject
1	V	13	Client	Hong Kong-Zhuhai-Macao Bridge
2		6	Client	Hong Kong-Zhuhai-Macao Bridge
3		4	Consultant	Shenzhen Qianhai New City Centre
4		13	Consultant	Shanghai World Expo
5		15	Consultant	Shanghai West Bund Media Port
6		17	University	Beijing Daxing International Airport
7		8	University	Shanghai West Bund Media Port
8		6	Research institute	Resettlement Housing Project in Nanbeikang Area of Jinan
9		4	Research institute	Xiong'an New Area
10	V	20	Research institute	Qilu Software Park
11		6	Research institute	Qingdao Metro Line 4
12		4	Contractor	Jinan Rail Transit Line 4
13		4	Contractor	Qingdao Metro Line 4
14	V	15	Contractor	Xiong'an New Area
15	V	12	Contractor	Sichuan-Tibet Railway
16	V	18	Contractor	Shanghai West Bund Media Port
17		6	Contractor	Resettlement Housing Project in Nanbeikang Area of Jinan
18		9	Supplier	Guangxi Nanning East Railway Station Infrastructure Facility Program
19	V	16	Supplier	Jinan Rail Transit Line 4
20	V	8	Supplier	Qingdao Metro Line 4
21		7	Designer	Xiong'an New Area
22	V	10	Designer	Beijing Daxing International Airport
23	V	9	Designer	Resettlement Housing Project in Nanbeikang Area of Jinan
24	V	15	Designer	Shenzhen Qianhai New City Centre
25		6	Designer	Qingdao Metro Line 4

Table 1 Possible innovation outcome measures

Innovation outcome measures	References	Description	Suitability (0-No, 1-Yes)	Coding
Reduction in project duration	Ozorhon et al. (2016); Ozorhon and Oral (2017); Noktehdan et al. (2019)	Completing the megaprojects ahead of schedule	1	C1
Reduction in project cost	Ozorhon et al. (2016); Fernando et al. (2019); Noktehdan et al. (2019); Slaughter (1998)	Reducing the costs used in completing the megaprojects	1	C2
Revenue growth due to new products or services	Fernando et al. (2019); Maghsoudi et al. (2016c)	New products or services can help firms to gain more monetary income	1	C3
Aesthetic in appearance and façade	Maghsoudi et al. (2016a); Maghsoudi et al. (2016c)	Making buildings more beautiful and good-looking	1	C4
Increased productivity	Ozorhon (2013); Ozorhon et al. (2016); Ozorhon and Oral (2017)	Innovations can help increase production efficiency	0	
Consistency with the neighbourhood	Maghsoudi et al. (2016a); Maghsoudi et al. (2016c)	Be in harmony with the neighbourhood and respect their opinions and local custom	0	
Improvement of people's life quality	Ozorhon (2013); Ozorhon et al. (2016); Noktehdan et al. (2019)	New/improved products can change the lifestyle of people and improve people's lives	1	C5
Improvement in social space	Maghsoudi et al. (2016a); Maghsoudi et al. (2016c)	Increasing public space, green space, et al	1	C6
Carbon emission reduction and more environmentally friendly production	Ozorhon (2013); Ozorhon and Oral (2017); Maghsoudi et al. (2016a); Noktehdan et al. (2019)	By adopting new production methods to reduce carbon emissions and achieve environmentally friendly production	1	C7
Service improvement	Maghsoudi et al. (2016a); Ozorhon (2013); Roehrich et al. (2019)	Creating new methods and adopting new visions can enhance service performance	0	
National or firm reputation and image enhancement	Ozorhon (2013); Ozorhon et al. (2016); Fernando et al. (2019)	Creating world-class technologies can help improve national or firm's reputation and image	1	C8
Increase in stakeholders' satisfaction	Maghsoudi et al. (2016c); Ozorhon et al. (2016); Fernando et al. (2019)	By controlling and managing influence factor on innovation to achieve expected goals and increase participants' satisfaction	1	C9
Improvement in product quality	Maghsoudi et al. (2016a); Ozorhon (2013); Fernando et al. (2019)	Innovation can improve the deficiencies of existing products and improve product quality	1	C10
Improvement in project safety	Maghsoudi et al. (2016a); Maghsoudi et al. (2016c)	By creating new construction techniques or methods to improve the construction workers and buildings' safety	1	C11
Creation or improvement in construction technology	Brockmann et al. (2016); Maghsoudi et al. (2016a); Slaughter (1998)	Creating or improving technologies related to project implementation, e.g. prefabricated technology	1	C12
Creation or improvement in the construction process	Brockmann et al. (2016); Ozorhon (2013);	Creating or improving process related to planning or delivering projects, e.g. the contractor selection process, payment process, bidding, and tendering process, etc.	1	C13
Creation of new construction standards	Brockmann et al. (2016); Ozorhon (2013)	Establishing or improving standards for buildings' quality, safety, etc.	1	C14
Creation or improvement in contract form	Brockmann et al. (2016); Ozorhon (2013)	Making changes to the deficiency in the existing contract form or creating a new contract to meet megaprojects' specific requirements	1	C15
Creation or improvement in project management methods and theory	Brockmann et al. (2016); Maghsoudi et al. (2016c)	Creating or improving the discipline of project planning, organising, managing, e.g. adopting agile/lean construction	1	C16
Intellectual property (e.g. patents, publication, design)	Maghsoudi et al. (2015); Ozorhon et al. (2016)	Gaining patent authorisation for the creation or publishing of new books on the megaprojects to make more money	1	C17
Experience gaining and knowledge sharing	Maghsoudi et al. (2016c); Bagherzadeh et al. (2020)	Experience and knowledge gained by a firm can be used in future megaprojects and shared among participants	1	C18
Market penetration and growth	Ozorhon (2013); Ozorhon and Oral (2017)	Helping firms to gain more market share	1	C19
Creation or improvement in financial arrangements	Maghsoudi et al. (2016a); Maghsoudi et al. (2016c)	Creating or improving financial method for the megaproject, e.g. debt, private money, equity	1	C20
Improvement in human resources	Ozorhon (2013); Ozorhon et al. (2016); Ozorhon and Oral (2017)	Improving the mechanism for recruiting and training talents	0	
Improvement of business structuring	Maghsoudi et al. (2016a); Maghsoudi et al. (2016c)	Improving the business methods used in the megaproject, e.g. option development, improving project initiation	0	
Improvement of firm and organisation's competitiveness	Maghsoudi et al. (2016a); Fernando et al. (2019); Maghsoudi et al. (2016c)	Help firms master the core technology or knowledge to rival competitors	1	C21
Achievement of established goals and objectives	Pellicer et al. (2014); Maghsoudi et al. (2016a)	Finishing megaprojects' goals or specific goals set by the client	0	
Future business collaborations with project participants	Ozorhon and Oral (2017); Maghsoudi et al. (2016a); Fernando et al. (2019)	Developing good relationships with other participants and forming a consortium to bid	1	C22
Enhancement of employee motivation	Pellicer et al. (2014); Maghsoudi et al. (2016a); Fernando et al. (2019)	Motivating employee to participate in innovation activities	0	
Identification of changes and new opportunities through the technology	Pellicer et al. (2014); Maghsoudi et al. (2016a)	Technology innovation can bring some opportunities, e.g. accessing overseas market	0	

Table 2 Adjacency Matrix of innovation outcome measures

Measures (i/j)	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22
C1	1							1	1												1	
C2		1						1	1												1	
C3			1					1	1												1	
C4			1	1					1								1				1	
C5					1				1													
C6					1	1			1								1					
C7		1			1		1	1	1		1										1	
C8								1	1												1	1
C9								1	1										1		1	1
C10			1		1			1	1	1						1	1	1			1	1
C11		1						1	1		1					1	1	1			1	1
C12	1	1	1	1		1	1	1	1	1	1	1				1	1	1			1	1
C13	1	1	1				1	1	1	1	1		1			1	1	1			1	1
C14	1	1	1	1		1	1	1	1	1	1			1		1	1	1			1	1
C15	1	1	1				1	1	1	1	1				1	1	1	1			1	1
C16	1	1	1				1	1	1	1	1					1	1	1			1	1
C17	1	1	1					1	1								1	1			1	
C18	1	1	1					1	1								1	1			1	1
C19								1											1		1	1
C20	1	1	1					1	1	1	1					1				1	1	
C21								1													1	1
C22									1													1

All zero entries are left blank.

Table 3 Reachability Matrix of innovation outcome measures

Measures (i/j)	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	Driving power
C1	1							1	1										1		1	1	6
C2		1						1	1										1		1	1	6
C3			1					1	1										1		1	1	6
C4	1	1	1	1				1	1								1	1	1		1	1	11
C5					1			1	1										1		1	1	6
C6	1	1	1		1	1		1	1								1	1	1		1	1	12
C7	1	1	1		1		1	1	1	1	1					1	1	1	1		1	1	15
C8								1	1										1		1	1	5
C9								1	1										1		1	1	5
C10	1	1	1		1		1	1	1	1	1					1	1	1	1		1	1	15
C11	1	1	1		1		1	1	1	1	1					1	1	1	1		1	1	15
C12	1	1	1	1	1	1	1	1	1	1	1	1				1	1	1	1		1	1	18
C13	1	1	1		1		1	1	1	1	1		1			1	1	1	1		1	1	16
C14	1	1	1	1	1	1	1	1	1	1	1			1		1	1	1	1		1	1	18
C15	1	1	1		1		1	1	1	1	1				1	1	1	1	1		1	1	16
C16	1	1	1		1		1	1	1	1	1					1	1	1	1		1	1	15
C17	1	1	1					1	1								1	1	1		1	1	10
C18	1	1	1					1	1								1	1	1		1	1	10
C19								1	1										1		1	1	5
C20	1	1	1		1		1	1	1	1	1					1	1	1	1	1	1	1	16
C21								1	1										1		1	1	5
C22								1	1										1		1	1	5
Dependence power	14	14	14	3	11	3	9	22	22	9	9	1	1	1	1	9	13	13	22	1	22	22	

All zero entries are left blank.

Table 4 Iteration of Reachability Matrix

Measure (Ci)	Reachability set: R(Ci)	Antecedent set: A(Ci)	Intersection set I(Ci)	Level
1	1,8,9,19,21,22	1,4,6,7,10,11,12,13,14,15,16,17,18,20	1	II
2	2,8,9,19,21,22	2,4,6,7,10,11,12,13,14,15,16,17,18,20	2	II
3	3,8,9,19,21,22	3,4,6,7,10,11,12,13,14,15,16,17,18,20	3	II
4	1,2,3,4,8,9,17,18,19,21,22	4,12,14	4	IV
5	5,8,9,19,21,22	5,6,7,10,11,12,13,14,15,16,20	5	II
6	1,2,3,5,6,8,9,17,18,19,21,22	6,12,14	6	IV
7	1,2,3,5,7,8,9,10,11,16,17,18,19,21,22	7,10,11,12,13,14,15,16,20	7 10 11 16	IV
8	8,9,19,21,22	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22	8,9,19,21,22	I
9	8,9,19,21,22	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22	8,9,19,21,22	I
10	1,2,3,5,7,8,9,10,11,16,17,18,19,21,22	7,10,11,12,13,14,15,16,20	7,10,1116	IV
11	1,2,3,5,7,8,9,10,11,16,17,18,19,21,22	7,10,11,12,13,14,15,16,20	7,10,1116	IV
12	1,2,3,4,5,6,7,8,9,10,11,12,16,17,18,19,21,22	12	12	V
13	1,2,3,5,7,8,9,10,11,13,16,17,18,19,21,22	13	13	V
14	1,2,3,4,5,6,7,8,9,10,11,14,16,17,18,19,21,22	14	14	V
15	1,2,3,5,7,8,9,10,11,15,16,17,18,19,21,22	15	15	V
16	1,2,3,5,7,8,9,10,11,16,17,18,19,21,22	7,10,11,12,13,14,15,16,20	7,10,1116	IV
17	1,2,3,8,9,17,18,19,21,22	4,6,7,10,11,12,13,14,15,16,17,18,20	17,18	III
18	1,2,3,8,9,17,18,19,21,22	4,6,7,10,11,12,13,14,15,16,17,18,20	17,18	III
19	8,9,19,21,22	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22	8,9,19,21,22	I
20	1,2,3,5,7,8,9,10,11,16,17,18,19,20,21,22	20	20	V
21	8,9,19,21,22	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22	8,9,19,21,22	I
22	8,9,19,21,22	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22	8,9,19,21,22	I