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A Benefits Prioritization Analysis on Adopting BIM Systems Against Major Challenges in Megaproject Delivery

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Purpose: This article presents a recent research and development experiment on benefits analysis for adopting building information modeling/management (BIM) systems in megaproject delivery across work stages with regard to the needs of project stakeholders. It focuses on a new approach to benefits prioritization to support decision making against major challenges in megaproject delivery.

Methodology: The study was underpinned by an extensive literature review on relevant research and practices across the world, and a questionnaire-based survey on the benefits from adopting BIM in megaproject delivery in Australia. In addition, this study yields new tools for value analysis with regard to the adoption of BIM systems in megaproject delivery, and this include a new calculation method for benefits prioritization, and a new value compass tool to support decisions making on BIM adoption.

Findings: Through the extensive literature review that covers multidisciplinary areas relating to the use of BIM, a set of generic hypotheses was formulated on the comparative level of technical value that various stakeholder groups are expected to achieve from adopting BIM systems in megaproject delivery. These hypotheses were tested by using the questionnaire-based survey. A new benefits prioritization approach was developed to identify the key benefits of BIM systems in megaproject delivery. In addition, a compass tool was also developed to visualize the status of value achievement across project stakeholders in dealing with major challenges in megaproject delivery.

Implications for Research and Practices: By using data collected from the Australian megaproject sector in addition to academic review in Australia, China, and United Kingdom, this experimental study revealed current professional perceptions on the benefits of adopting BIM systems in megaproject delivery in comparison with data and information reported by professionals concerning the adoption of BIM systems from both generic and specific point of view across multiple megaproject stakeholders.

Value: This article provides useful information for both academic research and practical services in the context of quantitative Cost-Benefit Analysis (CBA) on the adoption

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of BIM systems in megaproject delivery when major challenges on professional competence, budget, schedule and sustainability need to be seriously dealt with. Findings from this experimental study can inform value engineering practice at both strategic and tactic level with regard to adopting BIM systems in megaproject delivery.

Keywords: abductive reasoning, benefits prioritization, BIM, construction management, megaproject delivery, multiple source verification, project lifecycle

INTRODUCTION

This article describes the authors' recent efforts to a research and development experiment, called experimental study below, which focuses on a benefits prioritization analysis on adopting BIM systems with regard to effectively dealing with major challenges in megaproject delivery. In order to make a decent introduction, the authors of this article would like to begin with statements on five related aspects, including the aim and objectives of the experimental study, a brief description about the general characteristics of a megaproject, a summary on major technical challenges and the need for advanced solutions in megaproject delivery, a consideration on BIM-integrated megaproject delivery, and a short description about the structure of this article.

Aim and Objectives

This experimental study was recently conducted by the authors toward new benefits prioritization and visualization approaches to adopting building information modeling/management (BIM) systems in the process to tackle major challenges across life-cycle work stages in megaproject delivery. Under this overall aim, the experiment was deployed to achieve the following three objectives:

- A hypothesis-based pilot study on stakeholders' perceptions on the benefits to derive from adopting BIM systems in megaproject delivery,
- A tool for quantitative measure to prioritize the identified benefits from adopting BIM systems in megaproject delivery, and
- A tool for qualitative measure to verify prioritized benefits over identified major challenges in megaproject delivery.

It is essential for the research described here to make a contribution to the existing knowledge with a new understanding and method on value-oriented BIM in the context of megaproject delivery. As probably the first attempt to derive a benefits oriented solution to confront with major challenges in megaproject delivery with regard to technical enhancement through the adoption of BIM across life-cycle work stages, the research strategy has focused on two aspects on evidence and solution respectively. For evidence, including data and information, they need to be collected from megaproject practices. For solution, to be derived from research, it needs to be useful for megaproject practice in terms of effectively tackling major technical challenges (Chen, 2019) such as professional competence, overruns on budget and schedule, and megaproject sustainability. Based on these starting points, methodology for this research and development initiative was carefully considered to ensure the achievement of the aim and objectives.

In order to better describe the technical details of its strategy made for research and development in this experimental study, some key issues, which are highly relevant to the study, are first addressed below as background information, and these include the characteristics of megaproject, a generic view on major challenges and the need for advanced solutions in megaproject development and operation, and BIM-integrated megaproject delivery.

Characteristics of Megaproject

A megaproject for societal and industrial development is a large-scale construction or redevelopment project, which typically costs over USD1bn and has substantial impacts on the entire megaproject profile covering social, technical, economic, environmental and political (STEEP) aspects/issues (Chen, 2007) across various project stages. In the construction sector, a megaproject is a large-scale capital project typically costing more than USD1bn (PricewaterhouseCoopers [PwC], 2014), and an important set of major projects, which may cost over USD100m each. From a general point of view, megaproject development and operation aims to significantly improve public services and deliver more dependable infrastructure systems that can last for generations under the agenda of sustainable development.

A megaproject is often delivered by project-driven consortiums leading large scale investments into the

Abbreviations: AIB, Australian Institute of Building; BER, Berlin Brandenburg Airport (project); BIFM, British Institute of Facilities Management; BIM, Building Information Model/Modeling/Management; BSI, British Standards Institution (British standards); CAD, computer aided design; CBA, cost-benefit analysis; CIAT, Chartered Institute of Architectural Technologists; CIC, Construction Industry Council; CIOB, Chartered Institute of Building; CMAA, Construction Management Association of America; CMBOK, construction management body of knowledge; COST, Cooperation in Science and Technology; CPD, Central Procurement Directorate (Department of Finance, Belfast); CRC, Cooperative Research Centre for Construction Innovation (Australia); ERA, Environmental Risk Assessment; ICE, Institution of Civil Engineers; IPA, Infrastructure and Projects Authority; IPD, Integrated Project Delivery; LCC, The Legislative Council Commission (Hong Kong); LNG, Liquefied Natural Gas (project); MCDA, Multi-Criteria Decision Analysis; MTR, Mass Transit Railway Corporation Ltd. (Hong Kong); NBS, National Building Specification; OECD, Organization for Economic Co-operation and Development; PB, prioritized benefit; PMBOK, Project Management Body of Knowledge; PMI, Project Management Institute; RIBA, Royal Institute of British Architects; RAM, Risk Analysis Method; ROI, Return on Investment; SCL, Shatin to Central Link project (Hong Kong); RTSC, Railway and Transport Strategy Centre (Imperial College London); STEEP, Social, Technical, Economic, Environmental and Political (aspects/issues/risks); SWIFT, Structured What If Technique; TMR, Department of Transport and Main Roads (State of Queensland, Australia); UN, United Nations; WBG, World Bank Group.

transformation of local built environment. On the theoretical side, megaprojects are usually characterized by technical complexity, large budgets on resources use at various development and operation stages, and extended timeframes for planning, design, construction and operation (Altshuler and Luberoff, 2003), and simultaneously require excellent relationship development (Hart, 2015) among public and private investors, and other project stakeholders.

It is because of the much bigger scale of megaproject in comparison with small-scale construction projects, technical challenges and difficulties encountered by participants upon project delivery at various interconnected work stages are significantly increased as a result of the huge demand on resources and sustainability (Brookes et al., 2014; Boateng et al., 2017; Chen et al., 2017). Consequently, there is always the need for developing collaborative working relationships across the large specified complex and dynamic resources supply network in a consistent and persistent way through professional project management. Through learning lessons from past experiences in megaproject delivery across the world (Chen, 2019), it is anticipated that dedicated professional management underpinned by dependable team-wide expertise, powerful technical solutions, and constant commitment and momentum can enable effectiveness, efficiency and economy, which could be deemed as the best value for money, at various working stages throughout the project lifecycle. It is therefore a theoretical requirement to equip the management team with advanced technical solutions to tackle challenges in megaproject development and operation.

Major Challenges and Need for Advanced Solutions in Megaproject Delivery

The retrospective practice on megaproject at an international scale has accumulated numerous lessons on theoretical challenges in project delivery across the lifecycle. According to recent research, the trend of megaproject development across industry sectors worldwide is moving increasingly in past several decades (Merrow, 2011; Shauk, 2013; Flyvbjerg, 2017), and many megaprojects have experienced significant cost overruns, delays and various conflicts (Fiori and Kovaka, 2005; Greiman, 2013; Flyvbjerg, 2014). In Australia, for example, Chamber and Kitney (2011) found that although there were 15 megaprojects approved since year 2000, only one project, i.e., the ConocoPhillips' Darwin liquefied natural gas project (USD3.3bn), reached production on both time and budget, while the Australian resources sector was hit by more than $8bn in megaproject cost blowouts between 2005 and 2010. In fact, significant time and cost overruns encountered in megaproject delivery have become a phenomenon unfortunately rather than an exception. Lessons learnt from observations, literature review, and abductive reasoning about this phenomenon in many cases indicated that the delivery of megaproject is a remarkable technical challenge for professionals who are unfamiliar with, and/or unwell informed by, and/or well-prepared to deal with complicated details in megaproject delivery. Major challenges in megaproject delivery can be divided into three categories on people/workforce, product/production, and processes respectively (Chen, 2019), and consequently four major technical challenges in megaproject delivery can be identified and interpreted on the needs for

- Sound professional competence, with regard to competitive leadership and workforce through an effective use of the CMBOK;
- Reasonable budget, with regard to effective process control on the use of resources;
- Reliable schedule, with regard to efficient process control on the use of time; and
- Substantial sustainability, with regard to a dependable built environment for operational value in a designed lifespan.

Generally speaking, it is always a practice-oriented requirement for not only professionals working on, but also academics undertaking research into megaproject engineering and management in terms of advanced technical solutions through innovation and transformation, which can help actions to tackle these major challenging problems. Those technical solutions underpinned by the effective use of data, information and professional knowledge (Bishop, 2012) could help stakeholders effectively achieve strategic value (Ewejea et al., 2012), which are well-anticipated (National Audit Office [NAO], 2013) from the development and operation of megaproject.

BIM-Integrated Megaproject Delivery

Generally speaking, advanced technical solutions to enhance the performance of megaproject delivery are expected on both effectiveness and efficiency to reduce the risks of occurrences of mistakes, which may be repeatedly made across the entire process of using resources in megaproject development and operation. In this regard, it is necessary for these solutions to be developed against various reasons for making similar mistakes or the persistent underperformance on expenditures and schedule in megaproject delivery. In another word, advanced technical solutions should aim at their capacities to confront with the four identified major challenges against dependable megaproject delivery toward well-defined targets across work stages.

Through lessons learnt from megaproject management in representative cases, strategic priorities, which consist of the development of leadership capability and professional competences (Kwegyir-Afful, 2018; Merrow and Nandurdikar, 2018), have emerged as vital for megaproject delivery. The need for enhanced project management systems, which are supported by innovative technical solutions such as BIM systems (Crotty, 2012; Chong et al., 2016; Department of Transport and Main Roads [TMR], 2017; Hosseini et al., 2018), has been highlighted recently in order to improve communication and collaborations among stakeholders across various megaproject stages. It is therefore verified as the necessity to further specify the value of BIM, which has been identified in research to have dramatic value in terms of lifecycle project cost reductions and time saving (Bryde et al., 2013), effective and efficient communication and collaborations (Liu et al., 2017), enhanced safety management (Martínez-Aires et al., 2018), and many other issues as summarized by Hosseini et al. (2018), on the road to tackle the stubborn problem of significant time and cost overruns and other major challenges through a BIM-integrated megaproject delivery with regard to some research initiatives in transport projects (Blanco and Chen, 2014) and large-scale building projects (Kim et al., 2017), etc. This is an essential consideration for a new research into the multidisciplinary value analysis of BIM in megaproject delivery under the agenda of sustainability inside the built environment.

Structure of This Article

From the presentation structure point of view, this article firstly describes research background to justify research aim and objectives through a review of relevant literature. It then describes six BIM-focused hypotheses on its key value for major megaproject stakeholders in dealing with major challenges, and these hypotheses were derived from an in-depth review of related literature, including case studies from Autodesk (2011), one of the most influential leaders in BIM technology development across the world, and PricewaterhouseCoopers [PwC] (2018), one of the leading services providers in the provision of BIM Level 2 benefits measurement methodology to public sector capital assets, with regard to how the benefits of BIM have been realized in practice and the authors' judgments on the benefits of BIM can bring to megaproject stakeholders. A questionnaire-based survey was further employed to obtain details about professionals' views on these hypotheses and the benefits of using BIM in megaproject delivery, and it was conducted to the Australian megaproject sector for an experimental study. Based on these research activities, this article provides a unique approach to prioritizing the benefits of using BIM in megaproject delivery in order to eventually achieve a ranking list, which informs both megaproject stakeholders and academic researchers, of the benefits of BIM and how to achieve better megaproject management within BIM-integrated work environment.

It is expected that the process and findings from this experimental study reported in this article could be useful for further research and practice in the utilization of BIM in megaproject delivery, and the benefits prioritization approach could be useful prior to holistically quantifying it benefits (PricewaterhouseCoopers [PwC], 2018) in the audit of megaproject development and operation. In addition, it is also expected that the new concept of BIM Value Compass, which was developed for mapping the strength of the project team in dealing with major challenges through the use of BIM in megaproject delivery, could also be useful for further research and development.

BACKGROUND

A literature review was initially conducted to justify the described research into multidisciplinary value-oriented analysis of adopting BIM systems in megaproject delivery, and it focuses on two main issues, including awareness and adoption, and costs and benefits. This literature review helped to derive a list of generic benefits upon adopting BIM in construction projects. Findings from literature review were also used to first establish a set of theoretical hypotheses about BIM's value for megaproject delivery, and then conduct a questionnaire-based survey to detect relevant professional perceptions on BIM's usage and value. In order to test theoretical hypotheses, and to demonstrate the effectiveness of a new benefits prioritization approach, which was developed from this experimental study, the questionnaire-based survey has been conducted in this experiment to collect relevant information from professionals who are experienced in megaproject delivery in various locations in Australia, China, and United Kingdom.

A brief description on two main aspects is given below regarding the reason for this experimental study in the context of adopting BIM in construction management, and these include

- Awareness and adoption;
- Costs and benefits.

Awareness and Adoption

BIM, as a multidisciplinary professional approach and an advanced technical solution for construction project delivery across work stages, has become a mainstream practice with a cutting-edge technological perspective in the global construction industry (Race, 2013), and professional interest has increased, together with BIM integrated construction practices occurring globally. For example, the National Building Specification [NBS] (2012–2019), which is part of RIBA Enterprises Ltd. owned by the Royal Institute of British Architects (RIBA) in United Kingdom, found from its annual survey that the awareness and usage of BIM is now nearly universal, and had risen from 58% in 2011 to 79% in 2012, 93% in 2013, 95% in 2014, 96% in 2015 and 2016, 97% in 2017, 99% in 2018, and 98% in 2019 across the entire construction supply chain. This series of NBS annual survey was supported by BIM-oriented organizations, including the British Standards Institution (BSI),

TABLE 1 | BIM related observations on LinkedIn.

Date	Amount	Period from baseline (month)	Increases (%)
Observation 1: Number of BIM related groups			
31/07/2016	821	Baseline	Baseline
17/03/2019	1,180	32	43.7
30/06/2019	1,219	35	48.5
18/03/2020	1,597	44	94.5
Observation 2: Members of the BIM Experts group			
31/01/2015	34,435	Baseline	Baseline
31/08/2016	51,937	19	50.8
31/08/2017	60,699	31	76.3
17/03/2019	67,814	50	96.9
30/06/2019	69,351	53	101.4
18/03/2020	76,590	62	122.4

(1) Primary data were collected online from LinkedIn website. (2) Calculations for Period and Increases were in comparison with the start date of observation on LinkedIn.

the Chartered Institute of Architectural Technologists (CIAT), the Chartered Institute of Building (CIOB), the Landscape Institute, Association for Project Safety, RIBA, the Construction Industry Council (CIC), and the Constructing Excellence. In addition, constant increases (see **Table 1**) identified on LinkedIn from the authors' observations in relation to BIM related groups, and the membership of BIM Experts group have also indicated the width and depth of adopting BIM systems in construction practices across the world. It was therefore expected that the wide awareness of value-driven BIM usage by professionals could significantly transform construction management from individual data collecting activities to integrative date driven processes in megaproject delivery.

In terms of technical awareness and the adoption of BIM among project stakeholders, survey results from published research suggest noticeable variation over the past decade. Young et al. (2008) found from their worldwide survey that 90% of respondents in architecture discipline and 85% of all respondents perceived themselves to be adequately trained in BIM; whilst construction contractors reported themselves to be the most sophisticated BIM users, with 46% of respondents defining themselves as advanced or expert users. In contrast, Gu and London (2010) found from their survey in Australia that architects were the most active parties in BIM adoption, whereas construction contractors and project managers were more likely to view BIM as a data management system, while facilities managers were to typically perceive BIM as a project information system. Based on case studies from 35 projects worldwide in the use of BIM, Bryde et al. (2013) emphasized the need for cost-benefit analysis (CBA), awareness raising, and education and training in BIM usage, in terms of its benefits to lifecycle project cost reduction and time savings. According to several major survey-based industry reports, including

- The series of annual national BIM reports by National Building Specification [NBS] (2012–2019) in United Kingdom,
- The McGraw Hill Construction reports (Bernstein et al., 2014a,b) on the business value of BIM for construction in major global markets, and
- The Dodge annual report (Jones and Laquidara-Carr, 2017) on the business value of BIM for infrastructure in France, Germany, United Kingdom, and United States.

It is apparent that experiences on BIM were limited among project stakeholders, and their perceptions of what BIM can offer in addition to the skills required upon applications are still evolving via extensive adoption as described by Kiziltas and Akinci (2010), Leite et al. (2011), Becerik-Gerber et al. (2012), Luth et al. (2014), Lee et al. (2015), Lee and Yu (2016), and Jin et al. (2017) based on their individual research into the use of BIM across interconnected project stages at international scale. It has been further noticed that there has been a lack of specific research into detecting the awareness and adoption of BIM in the megaproject sector.

Costs and Benefits

It was found from the literature review that a positive correlation is likely to exist between adopting BIM and its value as recognized by project stakeholders in terms of essentials (cost, quality, and time, etc.) for project efficiency (Barlish and Sullivan, 2012), although the expenditure on BIM systems may not be always increasing (JBKnowledge, 2018). The background of such a positive correlation has informed this experimental study in terms of making and justifying major challenge oriented hypotheses and developing tools for the prioritization and verification of identified benefits from BIM adoption in megaproject delivery.

As BIM is an evolving useful engineering theory and advanced technical solution to the construction industry, it is possible that inexperience and deficiency in adoption, rather than a lack of value, may be reasons for fast widespread awareness but less effective usages (Holzer, 2011; Ford, 2018) despite of mandated adoption orders. This view point is reflective to findings from industry-wide BIM surveys led by Young et al. (2008, 2009) who emphasized that users' view on BIM's value can improve significantly after they gain experiences in its usages; the concept of return on investment (ROI) (Bernstein et al., 2014a,b) was also introduced in these surveys to assess related practices, and it was found that there are proportional shares of BIM related costs across project stakeholders and this is encouraging for them indeed to adopt BIM according to Gerber and Rice (2010) who found that the cost of BIM was primarily borne by architects and engineers instead of construction contractors and project managers, and it was believed to be difficult to pass the cost of implementation back to the client. Consequently, as founded by Howard and Bjork (2008), in most cases the client is the main beneficiary of BIM adoption, and designers achieve a lower level of overall value as any benefits achieved are offset by the costs outlaid. Facilities managers on the other hand are likely to achieve the second most benefit from adopting BIM (Becerik-Gerber et al., 2012), although Gerber and Rice (2010) made no reference to facilities managers being adversely affected in terms of their expenditures on BIM. Facilities managers are potentially able to achieve a level of BIM value without being adversely impacted by tangible and non-tangible costs, as determined by Suermann and Issa (2009) when evaluating industry perceptions. Whilst both of the needs for BIM and the costs of BIM adoption by project stakeholders are obviously different, it can be easily recognized that they may perceive the value of BIM at different levels. It has been also noticed that there is currently limited research to date that has explored the variances in perceived BIM value across disciplines in megaproject delivery, although the topic has gained momentum in more recent years.

According to an extensive literature review conducted in this study, a list of 14 possible main benefits, as shown in **Table 9**, was identified from research and practices in adopting BIM systems on megaproject delivery with regard to its major challenges. These benefit items have been further used to build a set of theoretical hypotheses about BIM adoption in megaproject delivery; in addition, a further review was introduced for the purpose of professional justification through a pilot study using questionnaire-based survey, which was sent to invited professionals who have extensive knowledge and experiences in megaproject delivery in Australia, China, and United Kingdom. This article summarizes their perceptions on the value of BIM in megaproject delivery.

METHODOLOGY

The methodology adopted for this experimental study is the integrative use of literature review, questionnaire-based survey, case studies, and analytic tool development (see **Figure 1**), and has been implemented through five stages of rigorous and deductive research (Robson, 2011), namely including developing a hypothesis on the relationship between variables, establishing ways to measure the hypothesis, testing the hypothesis, analyzing the outcome, and confirming or modifying the new theory about the value of BIM adoption in megaproject delivery. In order to clarify the specific use of individual methods, **Figure 1** illustrates the methodological roadmap adopted to achieve given objectives in the process of this experimental study. Details of how these methods were collectively utilized in the research and development process are further described below.

Literature Review

The literature review was adopted to analyze evidence collected from practices and research into BIM usage and their impacts to major stakeholders in megaproject development and operation. This has enabled an adequate justification of research aim and objectives upon a sound understanding of relevant background, and an establishment of reliable hypotheses; and led to an extensive review of current literature on the value of BIM with regard to the need for further research into value-driven usage of BIM systems across project-wide disciplines in megaproject delivery. For megaproject development and operation in Australia, for instance, there is an increasing trend with huge investment on infrastructure development (Commonwealth of Australia [CoA], 2018) and an engaging policy on BIM adoption (Australian Institute of Building [AIB], 2013). The literature review in this experimental study covers background information focusing on:

- A value-oriented multidisciplinary analysis of adopting BIM to support collaborative working in construction projects; and
- A hypothesis-oriented theoretical analysis of adopting BIM across major project stakeholders in construction and redevelopment.

The main reason why it was expanded to the whole range of projects instead of megaproject only is that there was not sufficient research dedicating to BIM usage in megaproject delivery, and it is assumed that a review onto small-size projects can effectively inform an in-depth understanding on megaproject, which could normally be a cluster of elemental projects with smaller sizes.

The literature review conducted in this study has two main outcomes, including the hypotheses and the benefits of BIM adoption in megaproject delivery. Findings from literature review focusing on the value of BIM adoption were incorporated with considerations about the characteristics in relation to major challenges of megaproject delivery, and the consistent scenario and trend in construction management toward enhanced collaborative working among project participants. Via such a process, a set of generic hypotheses, which are presented in **Table 2** in the format of a theoretical description, was eventually established. These major challenge oriented hypotheses have been further verified through the use of evidence from practices.

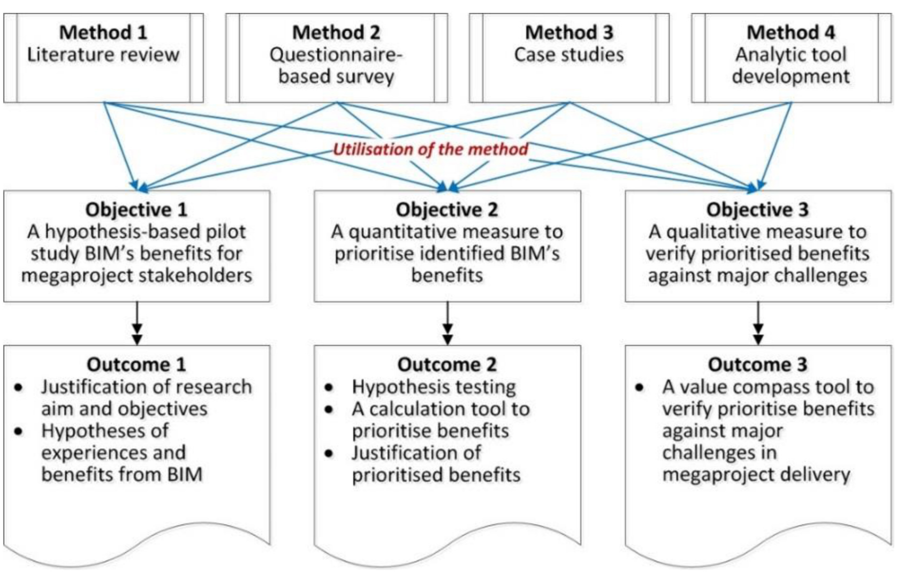

FIGURE 1 | Methodology established for research and development.

TABLE 2 | Hypotheses on megaproject stakeholders' experiences on BIM and its key value.

Megaproject stakeholders[1]	Code	Hypotheses[2]
Client/Developer	H1	A Client/Developer can always achieve the most value on higher-quality predictable outcomes from adopting BIM throughout the project lifecycle in comparison with other project stakeholders with regard to enabling cross-functional project teams to share project-based data and information. It is expected that the adoption of BIM systems can help the Client/Developer to tackle major challenges in a holistic manner.
Specialist Consultant	H2	Specialist Consultants have begun adopting BIM to become experienced users with regard to the effectiveness, efficiency and economy of collaboration and information sharing throughout project lifecycle. It is expected that the adoption of BIM systems can help the Specialist Consultant to tackle major challenges in a partial manner on an individual basis with regard to their various specialisms.
Construction Contractor (Main contractor and its sub-contractor)	H3	Construction Contractors perceive the value of BIM for them to be more than designers in terms of constructability issues, but less than clients with regard to the return on investment (ROI). It is expected that the adoption of BIM systems can help the Construction Contractor to tackle major challenges in a partial manner on an individual basis with regard to their specific specialisms on construction engineering and management.
Design Contractor (Design firm/team)	H4	Designers with more experiences in design and coordination perceive the value of BIM, as a holistic design approach, to be more than those with less experiences through project lifecycle. It is expected that the adoption of BIM systems can help the Design Contractor to tackle major challenges in a partial manner on an individual basis with regard to their specific specialisms on design and coordination.
Facilities Manager	H5	Facilities managers are beneficiaries of projected BIM systems adopted by other stakeholders and can achieve great value for both clients and themselves from adopting BIM at operation stage. It is expected that the adoption of BIM systems can help the Facilities Manager with relevant data and information being collected to tackle major challenges in a partial manner with regard to their specific specialism on facilities management.
Project Manager	H6	Project managers can achieve great value from adopting BIM on many aspects under the PMBOK framework in project delivery. It is expected that the adoption of BIM systems can help the Project Manager to tackle major challenges in a partial manner with regard to their specific specialism on project management.

Refer to The Chartered Institute of Building [CIOB] (2014) for description about different types of main project stakeholders. Hypotheses were made by using experiences and knowledge relating to megaproject stakeholders and case studies from Autodesk (2011), Arup (2014), McGraw Hill Construction (2014), Hardin and McCool (2015), Project Management Institute [PMI] (2016, 2017), and PricewaterhouseCoopers [PwC] (2018).

In addition, a list of BIM benefits identified for megaproject delivery was also summarized for a further justification through a multiple source verification process, in which feedback from experienced professionals in a questionnaire-based survey, and evidence from leading practitioners, including professional body and main contractor, have been used.

In this experimental study, as illustrated in **Figure 1**, literature review has been used to achieve the three objectives, and it has been used to facilitate the multiple source verification process for the study to yield convincing results that can be useful for further research and practices. Based on findings from literature review, a questionnaire was designed to facilitate new knowledge development regarding BIM's benefits in megaproject delivery, and a pilot verification of generic hypotheses, in relation to adopting BIM in megaproject delivery, was therefore conducted inside a multiple source verification process.

Questionnaire-Based Survey

A questionnaire-based survey was then used in this experimental study to elicit useful data from experienced professionals in order to test the set of hypotheses derived from literature review. In this experiment, as illustrated in **Figure 1**, the questionnaire-based survey has also used to achieve the three objectives. The questionnaire (see **Supplementary Data**) was designed under the six BIM oriented hypotheses, and was distributed to selected survey participants with a covering letter explaining the background and purpose of the research. Survey participants were asked to refer to one megaproject of their own experience where BIM was utilized.

In order to present the survey clear, concise and logical in front of potential respondents and therefore encourage a full completion and avoid simply leading the respondents via the order of the questions, the questionnaire was split into four distinct sections, including:

- Section on general information: profile of respondent, his/her company and the megaproject being referenced. This was intended to ensure that the inclusion criterion had been met and to allow for the appropriate categorization of data.
- Section on BIM and the company: profiles and perceptions on adopting BIM in individual megaprojects with the intention to gather data in relation to the value of BIM to the respondent's organization.
- Section on BIM and other stakeholders: respondent's perceptions of the value of BIM to other organizations on the referenced project.
- Section on contact details (optional): for future communication about survey results.

In addition to the design of this structure, the majority of questions were designed to be closed so as to allow for a quantitative analysis of the results, although some open questions were posed where it was identified that greater insight may be revealing. The finalized questionnaire was double checked prior to the survey to ensure that participants were not put off, questions were concise, the format of the survey was clear, and the time taken to complete the survey was kept to a minimum.

The criterion for selecting survey participants was the involvement of experienced professional individuals on at least one megaproject where BIM was utilized. Potential respondents were sourced via personal and professional contacts, including LinkedIn groups relating to Megaproject and BIM, and these include specific contacts from some major projects in Australia. The reasons for limiting the survey to Australia were a lack of relevant research to facilitate a global perception by comparison with existing literature, and a pilot study in Australia where there has been significant development recently in the megaproject sector (Commonwealth of Australia [CoA], 2018) with regard to the research for new knowledge about the value of adopting BIM in megaproject delivery in front of major challenges.

Case Study

Case study was further used for hypothesis verification in addition to the questionnaire-based survey in this experimental study. In the process, as illustrated in **Figure 1**, the case study has been used to achieve the three objectives. The reason to incorporate the case study is to overcome the shortage of professionals' opinions collected from the questionnaire-based survey. In addition, the incorporation of case studies can make the test of BIM oriented hypotheses more comprehensive in relation to its value throughout megaproject delivery.

There were two considerations on the selection of cases for study, and they are

- Representative megaprojects where BIM systems have been applied in project delivery, and
- Representative companies who have leadership positions in using BIM systems in megaproject delivery.

Based on the two considerations, relevant cases and technical details were collected from Google. Reliable information that have been collected for each selected cases consists of major stakeholders' annual reports, and details of BIM adoption in case megaproject.

The evidence collected in relation to case studies in this experimental study includes:

- Arup (2014): Building Design, 2010;
- Autodesk (2011): *Realizing the benefits of BIM*;
- Autodesk (2015): *The adoption of BIM systems in MTR Shatin to Central Link (SCL) project*;
- Alinea Consulting (2017): *Brent Cross regeneration project in London*;
- Brown (2018) and Swinerton (2018): *The adoption of BIM systems in the Oceanwide Center project in San Francisco*;
- Fiedler and Wendler (2015): *The Case of the BER Airport in Berlin-Brandenburg*;
- Hardin and McCool (2015): *BIM and Construction Management: Proven Tools, Methods, and Workflows*;
- Larsen and Toubro (2017): *The 73rd Annual Report 2017–2018*;
- PricewaterhouseCoopers [PwC] (2018): *BIM Level 2 Benefits Measurement: Application of PwC's BIM Level 2 Benefits Measurement Methodology to Public Sector Capital Assets; and*
- Skanska (2019a,b,c): *Building Information Modeling: benefits, collaboration, and projects.*

Tool Development for Benefits Prioritization

This experimental study aims at two tools with regard to its two objectives illustrated in **Figure 1**, and first tool is a new calculation method for benefits prioritization. The details about the two tools are presented in graphic and/or tabular format in the two sub-sections focusing on benefits prioritization and benefits verification respectively (see Sections "Benefit Prioritization and Verification" and "BIM Value Compass").

For benefits prioritization, in order to quickly detect megaproject professionals' opinions on BIM's value, data collected from the questionnaire-based survey were processed in a worksheet in Microsoft Excel by using its integrated statistical analysis functions. The data analysis also determined whether any key trends exist within and among various megaproject stakeholders in relation to the value of adopting BIM to inform the decision-making process for BIM adoption on future projects.

Besides statistical analysis, a new benefits prioritization approach, with two equations listed below, to prioritizing benefits identified for major project stakeholders on adopting BIM in megaproject delivery was developed with regard to benefits prioritization among existing methods (Hatton, 2008).

$$S_j = \sum_{i=1}^{5} (a_i \times P_i) \tag{1}$$

$$a_i = n_i / N \tag{2}$$

Equation 1 assigns scores to individual variables, which are BIM's benefits identified through literature review relating to megaproject delivery, where

- S_j is the score of variable j;
- a_i is the synthesized weight of the stakeholder i, and represents the proportion, which was defined by the number of survey participants from stakeholder i as expressed in Equation 2, of stakeholders participating the survey;
- P_i is the perception of stakeholder i, and is measured by the proportion (%) of positive responses to variable j among stakeholder i;
- i is the number of stakeholder types, and $i \in [1, 5]$ in this experimental study; and
- N is the total number of survey participants.

This benefits prioritization method is used in this experimental study to make a ranking list of BIM's benefits for stakeholders involved in megaproject development and operation, and it can be used for benefits prioritization (WBG and RTSC, 2017) and benefits management (Infrastructure and

Projects Authority [IPA], 2017) in BIM-integrated megaproject delivery. The use of this tool in this experiment has achieved a ranking list among 14 identified benefits due to BIM adoption.

Tool Development for Benefits Verification

A benefits verification in the context of the aim of the described experimental study is to show the level of individual benefits from adopting BIM in front of decision makers in megaproject delivery. The method chosen here to verify the benefits of BIM adoption was the radar chart, which has been extensively used for data and information visualization in many cases such as the SPeAR® (Sustainable Project Appraisal Routine) developed and adopted at Arup (2019), and is one of the most practical techniques recommended by the Department of Finance (Department of Finance [DoF], 2019b) for program and project management. A tool using radar chart was therefore developed in this experiment so as to visualize prioritized benefits among megaproject stakeholders in the context of adopting BIM systems to deal with the four major technical challenges. As illustrated in **Figure 1**, the development of this analytic tool was chosen to support two objectives.

In summary, the integration of the four methods, which are described in connection with **Figure 1** in this section, has demonstrated its effectiveness with regard to the completion of this experimental study with the three sets of expected outcomes. It was the lesson learnt from this experiment that the incorporation of case study in the process of justification of findings from questionnaire-based survey can not only overcome the lack of evidence that can be collected from a questionnaire survey, but also increase the reliability of such a justification by adding relevant evidence from important sources. It is therefore the authors' recommendation for future research to combine case study with questionnaire-based survey, for which the sample size won't be critical.

MAJOR CHALLENGE ORIENTED HYPOTHESES

One outcome from this study is hypotheses made for six types of key project stakeholders with regard to the adoption of BIM systems to deal with major technical challenges in megaproject delivery. The reason to establish these hypotheses is to support research, through making an entire set of theoretical descriptions about BIM adoption in megaproject delivery, which explores new technical solutions that can tackle four major challenges discussed in Section "Major Challenges and Need for Advanced Solutions in Megaproject Delivery." In fact, this anticipation is based on an assumption that the utilization of BIM systems can effectively support the project team in dealing with these major challenges. It is therefore expected that this hypothesis-based study can further facilitate a verification on whether and how the adoption of BIM systems would help professionals involved in megaproject delivery tackle major challenges, which are identified in previous research into learning lessons from megaproject practices.

In order to make a set of major challenge oriented hypotheses on the adoption of BIM systems in megaproject delivery, a further literature review about relevant background was conducted through quantitative studies in relation to the whole-life value of BIM for key project stakeholders, who are well defined by The Chartered Institute of Building [CIOB] (2014), including

- Clients/Developers (project investment decision-maker, project owner, and project sponsor),
- Specialist consultants (in areas such as design auditing; development surveying; facilities management; financing/leasing; health, safety and environment protection; insurance; legal; project planning; quantity surveying; specialists in construction management; and town planning; etc.),
- Design contractors (architects, engineers, and technology specialists),
- Project managers (client's in-house or outsourced specialist consultants), and
- Construction contractors (specialist contractors and/or their subcontractors, and specialist suppliers).

Under this sophisticated stakeholder structure, which is adoptable in megaproject delivery, this experimental study dedicated to making a set of new theoretical descriptions on the comparative level of BIM's value that various stakeholder groups are expected to gain in megaproject development and operation. The theoretical descriptions are given in detail under the structure of six hypotheses (see **Table 2**), which were put forward based on a set of specified BIM's benefits highlighted by Autodesk (2011) through additional case studies from several representative references as listed in Section "Case Study" and the note of **Table 2**, while there was also an incorporation of the authors' perceptions underpinned by their professional experiences and knowledge as well as advice gained from professionals across multidisciplinary areas relating to megaproject delivery. These hypotheses were further examined through a multiple source verification processes, including a questionnaire-based survey conducted among professionals who are experienced in megaproject delivery, and a series of real case studies.

The six hypotheses were made in the context of key project stakeholders' experiences in using BIM systems, and key value anticipated from adopting BIM systems upon megaproject delivery in reaction to major challenges. Hopefully this could form an original set of useful theoretical descriptions across various disciplines under the situation that it looks there is currently no such a summary available in relation to BIM adoption, although these theoretical descriptions need to be updated in the progress of BIM related practices. These hypotheses were further explained below, while a series of hypothesis verification, which is described in Section "Hypothesis Verification," was then conducted through the use of a multiple source verification process in this experimental study.

Clients

The demonstrable benefits of using BIM on clients' side (Computer Integrated Construction [CIC], 2013) have been identified through literature review and these include added value to varying degrees in terms of improved project data integrity, enhanced project performance analysis, improved communication and collaboration between project stakeholders, and multidisciplinary planning and coordination to varying degrees. The client or the owner/investor of a project is likely to benefit from all of these aspects, whether directly or indirectly. Therefore, a client can always achieve the greatest level of benefit from adopting BIM systems (Howard and Bjork, 2008) when compared to other project stakeholders, who may only achieve some benefits from BIM depending on their roles/positions in the project. Coupled with the fact that clients do not typically bear the costs associated with BIM (Gerber and Rice, 2010), it is a suggestion that clients are typically the driving force behind BIM adoption through setting it as a prerequisite to winning a project contract. Generally, as a value-adding tool BIM has been adopted by many clients, including those who are at the position to commission megaproject (The Chartered Institute of Building [CIOB], 2016). Consequently, hypothesis H1 (see **Table 2**) was formed with regard to the value of BIM for clients in megaproject development.

Specialist Consultants

The demonstrable benefits of using BIM on specialist consultants' side (Ahn et al., 2015) have been identified through literature review and these include added value to varying degrees in terms of Visualization, Cost estimating, Phase planning (scheduling), Site analysis, Programming, Existing condition modeling, Code review, and Contract review, etc. within the scope of their contracts.

A number of disciplines fall within the specialist consultant group (The Chartered Institute of Building [CIOB], 2014), including quantity surveying, project planning, and construction management. Although literature relating to the value of BIM systems to specialist consultants was limited, some analysis in relation to construction managers specifically was identified. Gerber and Rice (2010) found construction managers to be the least experienced users of BIM, often experiencing adverse impacts, albeit to a lesser degree than designers with regards to the costs outlaid. These findings suggest that construction managers may not perceive BIM to be a value-adding tool in the same way that other groups may. However, a recent market report (Bernstein et al., 2014a,b) highlighted that three quarters of construction companies had a positive ROI on their BIM program investment and have clear ideas about how to further improve ROI. This is a timely reflection of the fast pace of BIM adoption within the specialist consultant group across the global construction industry. Therefore, hypothesis H2 was formed with regard to the value of BIM for specialist consultants in megaproject delivery.

Construction Contractors

The demonstrable benefits of using BIM on construction contractors' side (Ahn et al., 2015) have been identified through literature review and these include added value to varying degrees in terms of Process visualization, Cost estimating, Phase planning, Site analysis and spatial coordination, Communication during construction, Prefabrication, Materials procurement, and Resource use analysis, etc. within the scope of their contracts.

Regarding the BIM integrated practice, Young et al. (2008) found that for that the construction contractor group are the lightest BIM users, with only half of construction contractors using BIM on less than 15 per cent of projects; however, Gerber and Rice (2010) reported that construction contractors are gaining experience in BIM faster than any other stakeholder group. According to this survey, construction contractors view themselves as the primary drivers of BIM, although in reality the results of the study found that it is architects who actually fill this role. It was reported by Young et al. (2008) that construction contractors view themselves as sophisticated BIM users, and have the most positive view on adopting BIM in relation to any other discipline examined, and consequently they suggested that as users gain experience in BIM, their view on its value can improve significantly. This has been further supported by research and development initiatives in relation to BIM maturity (McCuen et al., 2012; Mitchell et al., 2012; Smith, 2014; Central Procurement Directorate [CPD], 2015; Kassem et al., 2015b; McAuley et al., 2017; Ahankoob et al., 2018; Chen et al., 2018), although it was later found by Smits et al. (2016) that the impact of BIM maturity on project performance may be limited and it cautions against overoptimistic appraisals of BIM. This is particularly relevant to the construction contractor group, who clearly perceive BIM as a value-adding tool.

Given the increasing level of BIM adoption by this stakeholder group, and the fact that they increasingly are demonstrating positive actions in adopting BIM in many megaprojects (Institution of Civil Engineers [ICE], 2011–2017; Laing O'Rourke, 2014), it is expected that the value achieved by this group from adopting BIM will closely follow that of the client group with a positive ROI (Bernstein et al., 2014a,b). However, it is unlikely this group will surpass the client group in terms of the value achieved given the traditionally non-existent contribution of clients toward associated costs. Consequently, hypothesis H3 was made with regard to the value of BIM for construction contractors in megaproject delivery.

Design Contractors

The demonstrable benefits of using BIM on design contractors' side (Ahn et al., 2015) have been identified through literature review and these include added value to varying degrees in terms of Design visualization, Cost estimating, Phase planning, Site analysis, Communication and marketing, Design optimization analysis and review, Constructability study, and Energy use simulation, etc. within the scope of their contracts.

Given the level of adoption by design contractors, also called design firms, as well as the fact that they have not only continuously demonstrated strong interest in BIM as a value-adding tool despite the costs, but also been recognized as the driving force behind its implementation and use (Young et al., 2008; Gerber and Rice, 2010), it is expected that this group will identify the value achieved as a result of BIM as significant. However, it is, unlikely that they will surpass the client group in terms of value achieved, given that research has shown them to have a lack of understanding of how BIM solutions may apply across disciplines (Gu and London, 2010), coupled with the fact that this group has been typically found to bear the associated costs (Gerber and Rice, 2010). Consequently, the value achieved by this group is likely to be significant only in situations where they are able to streamline the costs associated with BIM as a result of their experience. Therefore hypothesis H4 was formed with regard to BIM's value for design contractors in megaproject delivery. This hypothesis is also supported by some other researchers, including Young et al. (2008) who found from extensive interviews with hundreds of professionals at 23 construction industry organizations in United States that users' view on its value can improve when they gain experience in BIM and Holzer (2011) who emphasized that users can only get substantial value out of BIM if they share information related to a project's delivery across the entire project team as early as possible.

Facilities Managers

The demonstrable benefits of using BIM on facilities managers' side (Cooperative Research Centre [CRC], 2007) have been identified through literature review and these include added value to varying degrees in terms of controlled whole-life costs and environmental data, better customer service, common operational picture for current and strategic planning, visual decision-making, and total ownership cost model, etc. within the scope of their contracts.

Total facilities management has become an important approach being adopted by major service providers (Chen, 2015), and it increases the demand on the use of BIM to facilitate informed practice, especially in the complex workplace environment created through megaproject development. According to Howard and Bjork (2008), facilities managers are probably the most significant beneficiaries of BIM systems after clients, although the actual adoption of BIM systems by facilities managers may currently be limited (Gu and London, 2010; Lopez, 2012) against perceived benefits for them (Edirisinghe et al., 2016). Facilities managers have been found to typically view BIM as a system which allows the access and retrieval of lifecycle data and information that are collected for the projected facilities management, although it was identified as a barrier to adoption of BIM by this group regarding the general lack of a process on the facilities management side for ensuring models to be updated with any variations which may occur during design, construction and/or operation. This suggests that facilities managers may be willing to use BIM systems if and when they are implemented and updated across all phases of a project lifecycle, such that when they do use BIM the data and information available is comprehensive and current, and appropriate for the needs of the facilities management team. Therefore hypothesis H5 was formed with regard to the value of BIM for facilities management firms in megaproject delivery.

Project Managers

The demonstrable benefits of using BIM on project managers' side (Bryde et al., 2013) have been identified through literature review and these include added value to varying degrees in terms of Better communication and collaboration, Organize the project schedule and budget, Budget control, Rapid analysis of different scenarios and feedback to owner, and Lean management, etc. within the scope of their contracts.

The literature relating to the value of BIM systems to project managers is limited, although some insight has been obtained in relation to this group's understanding of the functionality of BIM, with project managers typically describing BIM as an intelligent data management system (Gu and London, 2010); however, their views in relation to the value of BIM are largely unexplored. Consequently, hypothesis H6 was made based on the authors' perceptions with regard to the value of BIM for project management firms in megaproject delivery.

KEY FINDINGS AND DISCUSSION

This experimental study has made an attempt over several years to explore in an extensive way more appropriate interpretations on adopting BIM systems in megaproject delivery with regard to the aim and objectives. In order to describe outlets from this research and development initiative, a number of relevant issues are included here, and these include:

- Profile of survey respondents;
- Profile of reference megaprojects;
- Experiences with BIM;
- Total cost impact of BIM;
- Hypothesis verification;
- Benefit prioritization and verification;
- BIM and major challenges; and
- BIM Value Compass.

Profile of Survey Respondents

In order to reach a wide range of professionals who can provide appropriate answers to the research questions, a questionnaire was distributed amongst seven LinkedIn groups and through personal invitations to experienced professionals working in the megaproject sector in Australia and internationally between 2013 and 2017. For the survey, 24 professionals working on megaproject provided feedbacks, of which 22 data sets collected were eventually used for data analysis. Regarding data collection, the entire usable data set was originally collected from 22 respondents in 2013, and there was an additional revisit to the questionnaire-based survey with one expert in 2017 in order to double check and ensure results to be durable and useful after fast development on BIM over 4 years. Although the sample size was small, it represents useful and valuable data

TABLE 3 | Profile of survey participants from megaprojects in Australia.

Megaproject stakeholders	Number of survey participants	a_i*	Proportion (%)	Annual turnover (A$ millions)		
				Min	Mean	Max
Client	5	0.23	22.7	1,000.0	2,000.0	6,000.0
Specialist Consultant	6	0.27	27.3	5.0	701.7	1,500.0
Construction Contractor	1	0.05	4.5	10.0	10.0	10.0
Design Contractor	7	0.32	31.8	3.0	336.1	2,000.0
Project Manager	3	0.14	13.6	5,000.0	5,666.7	7,000.0

Refer to Equation 2 for the calculation method, and the method was used for ranking benefit factors in **Table 9.*

from the megaproject sector for this exploratory research. As all participants to the questionnaire-based survey and revisit have dependable experiences accumulated in megaproject practice and/or research in related areas, it is treated as high-quality data (Coviello and Jones, 2004) that were drawn using well-developed selection criteria and can result meaningful findings. In addition, a comparison study incorporating results from large-scale BIM survey conducted by The Chartered Institute of Building [CIOB] (2016) was used to redeem the small sample size encountered in the questionnaire-based survey.

Details of survey participants have been reviewed in order to make sure that the data and information that they provided are useful for further data analysis. **Tables 3**, **4** provide summaries of the profiles of the survey respondents. Among the 22 respondents, the majority (82%) represented design contractors, specialist consultants, and clients, with a maximum annual turnover of A$9.5bn in total. Most (91%) of the respondents had over five years professional experience, while more than half (55%) had over 10 years professional experience. It was therefore the authors' opinion that by consulting with some of these professionals that the respondent profiles ensure that this exploratory research can derive useful conclusions from the statistical analysis as there is sufficient information available elicited from reliable sources in the Australian megaproject sector.

There was only one completed survey received from a specialist contractor, and no responses were received from facilities managers. Consequently, it was difficult to reach any valid findings concerning the value of BIM for these two stakeholder groups, although insight was obtained from the specialist contractor who responded and by comments made by other respondents about BIM adoption by these two groups. Consequently, hypotheses H3 and H5 could not be tested and verified in this experimental study, and further research into the impact of BIM adoption in the facilities management group and the construction contractor group is therefore anticipated.

TABLE 4 | Respondents' industry experience by seniority.

Respondents	Proportion (%)				
	Industry experience (Years)				
	0–5	5–10	10–20	20+	All years
Project Support	9.1	4.5	–	–	13.6
Technical Professional	–	13.6	4.5	–	18.1
Manager	–	18.2	36.4	9.1	63.7
Executive Director	–	–	–	4.5	4.5
Total	9.1	36.3	40.9	13.6	99.9

TABLE 5 | Profile of reference megaprojects by type.

Type of reference megaproject	Percentage (%)	Tender price (A$ millions)		
		Min	Mean	Max
Mining and Resources	40.9	900.0	11,644.4	15,000.0
Transport	27.3	950.0	950.0	950.0
Buildings	22.7	264.0	756.8	1,100.0
Energy	9.1	250.0	875.0	1,500.0

The reference megaproject refers to projects that the survey participants undertook at the time of the research. The period of contracts was between 2 and 6 years for all projects referenced in this study.

TABLE 6 | Profile of reference megaprojects by cost.

Tender price of reference megaprojects (A$ millions)	Percentage (%)
(250, 500)	13.64
(500, 1,000)	40.91
(1,000, 5,000)	13.64
≥5,000	31.82

The contract period was between 2 and 6 years for all reference megaprojects in this experimental study.

Profile of Reference Megaprojects

The profiles of megaprojects referenced by the survey respondents are summarized in **Tables 5**, **6**. The majority (91%) of these reference megaprojects were projects for mining and resources, transport, energy, and buildings, and the mean tender price of individual projects was within the range of a megaproject defined by its cost while cost overruns were considered in this experimental study. The profiles of these megaprojects provide sufficient background information to confirm that useful conclusions can be derived from the data analysis, particularly in identifying further research in related areas.

TABLE 7 | Perceptions of capital cost and time savings by stakeholders.

Megaproject stakeholders	Proportion of previous BIM experience (%)	Perceptions on project profitability by adopting BIM in megaproject (%)	
		Cost saving	Time saving
Client	80	100	100
Specialist Consultant	100	33	50
Construction Contractor	0	–	–
Design Contractor	100	86	86
Project Manager	33	67	100

Experiences With BIM

Professionals were asked to identify if their company had worked with BIM prior to the megaproject referenced in the questionnaire-based survey. The majority (82%) of the respondents reported that they did have previous experience in using BIM, although four respondents identified the megaproject referenced as their company's first BIM integrated project. **Table 7** is made according to data collected from answers to questions about previous BIM experience, and project profitability by adopting BIM in megaproject. It has been further noticed from **Table 7** that three professional groups are most experienced in BIM, and they are clients, specialist consultants and design contractors.

According to survey results, most respondents (80%) from the client group had experience in BIM, and this result is supported by findings by Gerber and Rice (2010), who reported that the client is typically the driving force behind the implementation and use of BIM systems in construction projects. The questionnaire-based survey has also identified that BIM was a prerequisite to winning the contract for all but one of the megaprojects referenced.

All the respondents in the specialist consultant and design contractor groups mentioned that their companies had used BIM before, which indicated that BIM may be widely used by these two groups in megaproject delivery in Australia. This result supports hypotheses H2 and H4. However, as the specialist consultant group were not asked to identify their company's specific role as a specialist consultant (e.g., quantity surveying, project planning, or construction management), it is difficult to interrogate this further and further research into BIM value to specialist consultants is required. As there were no respondents who identified their companies to be a first time user of BIM in the referenced megaprojects, it was difficult to identify related elements in hypothesis H4, which calls for further research to compare BIM value upon varying levels of user experience.

The response from the construction contractor group, which consisted of only one small specialist construction contractor who had no perception of BIM, does not reflect the results of another survey described by Bernstein et al. (2014b), in which 61% construction contractors were reported as having over 3 years of BIM experience, and all construction contractors in Australia and New Zealand had BIM experience. This difference in the findings could be due to the fact that main construction contractors on megaprojects adopted BIM systems but sub-contractors did not doing so. It was therefore difficult to test hypothesis H3 due to the limited information available from this group.

Total Cost Impact of BIM

Responses to questions about the tangible and intangible cost impacts of BIM to companies engaging in megaproject delivery were amalgamated as a total cost impact for comparison. **Figure 2** illustrates the range and its mean of identified total cost impact for several major project stakeholders.

It was found from the survey that the cost impacts to specialist consultants and design contractors were generally fairly equal, although one respondent in the design group reported a slightly higher maximum. In addition, the client group was the only one which included respondents who identified their companies as having a nil cost impact upon adopting BIM. These results are consistent with findings from Gerber and Rice (2010), who found that the cost of BIM is primarily borne by designers and construction managers (who form part of the specialist consultant group for the purposes of this study), and to a lesser degree by construction contractors. While there was not enough data provided by construction contractors specifically, respondents from the project manager group identified the highest range in total cost impact upon using BIM.

It has been further noticed that research and practice to determine the exact costs of adopting BIM systems upon megaproject stakeholders has to date been limited, according to the case study by Alinea Consulting (2017) (12 November 2017) for the Brent Cross Shopping Centre redevelopment and refurbishment project (worth GBP1.4bn) in London, in terms of the cost estimation based on a BIM execution plan.

Survey results therefore provide valuable insight in terms of the necessity to optimize cost sharing among stakeholders in megaproject development and operation, and the optimized cost of using BIM systems by individual project stakeholders could therefore be within a more reasonable cost range. This view point is further supported by **Figure 3** in relation to BIM's total cost impact perceived from one stakeholder to other project stakeholders.

The finding on the total cost impact of adopting BIM systems to other megaproject stakeholders, as illustrated in **Figure 3**, gives an indication that designers were clearly perceived to be the bearers of the majority of BIM associated costs. This suggests that, whilst it is likely that designers often do bear a significant portion of the associated costs in specific megaprojects, the perception of other project stakeholders was that this amount is much higher than it actually is, as illustrated in **Figure 2**. It was noted that none of the respondents perceived facilities managers to be impacted in terms of the cost in any referenced megaproject, and this has an indication on cost sharing and liability ownership in terms of the adoption of BIM through integrated project delivery (IPD) (Construction Management Association of America [CMAA], 2010).

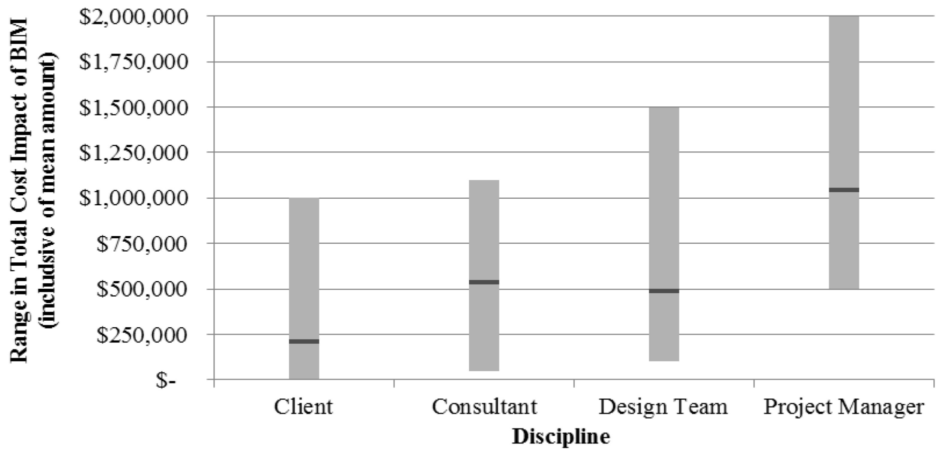

FIGURE 2 | Perceived total cost impact of BIM by individual project stakeholders (Day, 2013).

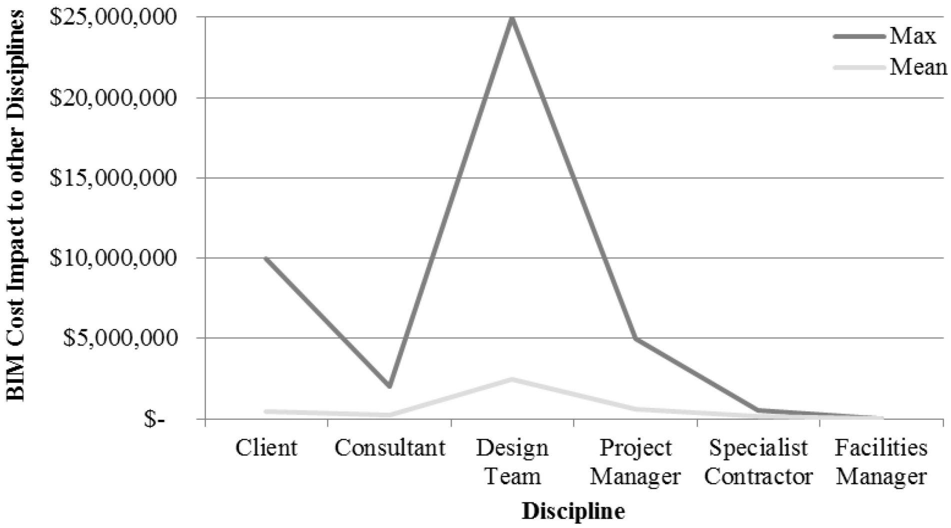

FIGURE 3 | Perceived total cost impact of BIM to other megaproject stakeholders (Day, 2013).

In summary, findings illustrated in the two figures, with supporting information from megaproject practice, can have meaningful implications on current concern and practice in relation to the total cost impact of BIM, and these include

- It is necessary to optimize cost sharing among stakeholders in BIM-integrated megaproject delivery.
- BIM Execution Plans can be typically useful to develop reasonable and accurate total cost ownership in megaproject development and operation.

These cost related implications have then informed this study in the process of hypothesis verification (see Section Hypothesis Verification), and then a scenario based examination of the BIM Value Compass tool (see Section "BIM Value Compass"), which is developed in this study to support decision making and/or strategic adjustment on BIM adoption with regard to prioritized benefits over major technical challenges, including cost overrun, among key megaproject stakeholders.

Hypothesis Verification

Hypothesis verification was conducted through the analysis of data and information collected from the questionnaire-base survey and further case studies focusing on representative megaproject and representative companies.

Hypothesis H1

Project profitability is impacted directly by both project duration and project costs for various stakeholders, especially major stakeholders such as the client. As summarized in **Table 7**, megaproject stakeholders had different perceptions of project profitability regarding BIM adoption. In relation to project costs, all respondents from the client group, and 86% of respondents from the design group identified that capital cost savings were achieved. In relation to project duration, all respondents from both the client and project manager groups identified that time savings were achieved, followed by 86% of respondents from the design group. These findings support hypothesis H1 that clients always achieve the most value from adopting BIM in comparison to other project stakeholders, and provide further insight into the potential value of BIM to specialist consultants, design contractors and project managers.

Hypothesis H2

All the specialist consultants had previous experience with BIM as summarized in **Table 7**. Although they reported a relatively low level of recognition of project profitability by adopting BIM in megaproject delivery, their perceptions support hypothesis H2. The survey responses revealed that specialist consultants had to export 3D coordination files to 2D CAD for construction when construction contractors did not have appropriate skills, working processes, and/or personnel to work with the design software, and this may have reduced project profitability for the specialist consultants.

Hypothesis H3

Although there was not enough data collected from specialist contactors to test hypothesis H3, the survey received useful comments from the client group to indicate partial support. For example, with regard to the cost impact of BIM to construction contractors, one client mentioned that BIM was introduced at the commencement of construction, and the main construction contractor and their sub-contractors engaged extra staff to create a BIM, which incurred additional costs of around A$500,000. Although this actually caused a delay to the commencement of some construction activities, the time and abortive cost for the rectification of clashes on site would have been much greater to the construction contractor if the model had not been created; however, there would have been more benefits to the client if BIM had been introduced during the design phase, as it was only a 'fix' introduced during construction with the primary purpose of assessing constructability. This comment supports hypothesis H3 for the clients, and it is inferable that the passive action taken by construction contractors has shown a good ROI and consequently, they will probably continue the BIM journey no matter whether it is required by the client and how much designers have done on their own in advance if BIM value can be expected to exceed the costs of adoption.

Hypothesis H4

Similar to the specialist consultant group, all the respondents in the design contractor group had previous experience of BIM, and the majority (86%) agreed on its positive impact on project profitability (see **Table 7**). Although hypothesis H4 is not sufficiently supported by this result in terms of the unclear variance in connection with BIM experience and perception among respondents, the difference between BIM experience and perception indicated that variance exists relating to BIM experience.

Hypothesis H5

There was no response from the facilities management discipline, and it was therefore not possible to test hypothesis H5 in this study. However, comments were given on BIM's benefits throughout project lifecycle. For example, one client mentioned that BIM was not fully detailed, and was therefore not further developed for facilities management in his project. This indicates a probably limited use of BIM at the operation stage of megaproject delivery at the present time as described by Bosch et al. (2015), Aziz et al. (2016), and Ashworth and Tucker (2017), although its value has been widely described (Kassem et al., 2015a; British Institute of Facilities Management [BIFM], 2017) for the practice of facilities management.

Hypothesis H6

It was found from the survey that BIM was not widely used among project managers, but their different perceptions of cost and time savings in terms of BIM adoption, as summarized in **Table 7**, significantly indicates that they recognize the value of BIM. This result supports hypothesis H6. In comparison with clients, specialist consultants and design contractors, it was apparent that the use of BIM did not appear to be prevalent among project managers in megaproject delivery. The reason why all the project managers confirmed that BIM is effective in saving time and the majority agreed that it can help to reduce project cost, is probably that their experience with BIM has shown its value on various aspects of megaproject management.

Case Studies

This experimental study has also incorporated case studies to verify hypotheses in addition to using data and information collected from the questionnaire-based survey. This approach is to ensure a better hypotheses verification in not only this study but also other questionnaire-based survey in order to eliminate the risk of partial substantiation when neither the sample size nor the sample profile (survey participants) were to be ideal in a questionnaire-based survey. The case study has been conducted in two ways, which focus on two representative projects (see **Table 8A**) and two representative companies (see **Table 8B**) respectively:

- For case studies on representative megaprojects, two projects were chosen with regard to the technical advance and geographic location of adopting BIM systems in megaproject delivery, and they are the Oceanwide Center project in San Francisco, United States; and the MTR Shatin to Central Link (SCL) project in Hong Kong, China.
- For case studies on representative companies, two companies were chosen with regard to their technical imitative and global practices on the adoption of BIM systems in megaproject delivery, and they are Skanska AB from Sweden, and Larsen & Toubro Ltd. from India.

The six hypotheses described in **Table 2** were put forward to focus on stakeholders' experiences in using BIM in relation

TABLE 8 | Case studies for hypothesis verification from representative projects and companies.

A: Project oriented case studies	
Representative project and key information about using BIM systems	**Verified hypotheses**
Oceanwide Center project, San Francisco, CA, United States	
Construction cost: USD1.60bn as at 02/11/2018 (Revis, 2018)	
The adoption of BIM systems based on cloud-based Revit platform (Brown, 2018; Swinerton, 2018):	
- Coordinating all design decisions in a centralized location.	H4
- Project stakeholders can have real-time access to and collaboration with the latest project information with increased visibility in terms of design quality.	All hypotheses
- Architects, engineers and contractors can use Revit to run through different scenarios, and to make changes across the model in real time.	H2, H3, H4
- BIM model was used to minimize risks on constructability and rework.	H2, H3, H4
- A realization of company-wide transition to continually improve processes and productivity.	All hypotheses
- Combining the tools with construction and design experience clearly saves time and money.	H3, H4
MTR Shatin to Central Link (SCL) project, Hong Kong	
Construction cost: HKD87.3bn as at 05/12/2017 (HKSAR Government, 2017)	
BIM was used to facilitate multidisciplinary design, coordination and construction in the complex rail extension project (Autodesk, 2015)	
- A BIM-oriented survey to collect detailed information from multiple stakeholder groups and adjacent utilities to ensure the feasibility of the designs with regard to accuracy, clarity, and quality.	All hypotheses
- The BIM approach helps the design team deal with technical issues in relation to civil engineering, architectural engineering, and services engineering at design stage.	H2, H4
- The BIM-enabled project timeline simulation helps the design team verify constructability, identify temporal clashes, and foresee potential risks.	All hypotheses
- The BIM approach helps the construction team deal with technical issues in relation to construability, planning, abortive work, and resources use at construction stage.	H3, H6
- The BIM approach helps speed up the checking process to improve the performance of project delivery.	H2, H3, H4, H6
- The BIM approach helps integrate information from adjacent built environment so as to enable the SCL team to analyze and control the adverse impacts.	All hypotheses

B: Company oriented case studies	
Representative companies and key information about using BIM systems	**Verified hypotheses**
Skanska AB, Sweden	
Ranked 9th by Engineering News-Record [ENR] (2018) on the list of 2018 Top 250 International Contractors	
- BIM is used to model plant movements and sequence clashes so as to ease logistics and save program time in piling and ground engineering (Skanska, 2019a).	H2, H3
- BIM is used to immediately respond to changes to the design or schedule, with any impact being clearly identified (Skanska, 2019b).	H3
- Benefits from adopting BIM systems (see **Table 10**)	All hypotheses
Larsen & Toubro Ltd., India	
Ranked 28th by Engineering News-Record [ENR] (2018) on the list of 2018 Top 250 International Contractors	
- The utilization of digital technologies to improve clients' experiences on quality, productivity, decision-making, and workforce throughout infrastructure project lifecycle (Larsen and Toubro, 2017; McKinsey and Company, 2018).	All hypotheses
- Digitalization is a focus area for quality and productivity improvement.	H3

to dealing with major challenges in megaproject delivery, and this set of hypotheses was only designed and used for this study to provide background information for benefits management in the context of benefit prioritization and verification for BIM adoption.

Benefit Prioritization and Verification

The benefit prioritization as a process aims to make a ranking list among identified benefits upon a specific construction project. While there is a lack of research into benefit prioritization upon BIM adoption at either individual levels or a hybrid level, this experimental study has made an initial effort through a questionnaire-based survey and evidence from practitioners to detect and verify a possibly generic list of prioritized benefits to inform decision making with regard to resources usage and the whole-life value in megaproject development and operation.

Tables 7, **9** show respondents' perceptions on the benefits from BIM across the referenced megaprojects. According to **Table 7**, all the respondents in the client group deemed that BIM can save capital cost and project time, while the majority (86%) of respondents from the design contractor group agreed with these savings. Although the specialist

TABLE 9 | Major challenge oriented benefits identified upon BIM adoption in megaproject delivery.

Rank	Benefits from adopting BIM systems	Connections/Relevance to major challenges			Respondents' perceptions (%)					Score[2]
		Competences	*Overruns*	*Sustainability*[1]	*Client*	*Specialist Consultant*	*Construction Contractor*	*Design Contractor*	*Project Manager*	
1	Enhanced design capacity	Design			80	100	0	100	100	90.91
2	Multidisciplinary planning and coordination		Schedule		80	67	100	100	100	86.45
3	Accuracy and consistency of data		Budget		60	67	100	100	100	81.91
4	Flexibility and ability to facilitate changes	Execution			60	67	100	86	100	77.45
5	Time savings		Schedule		100	50	0	86	100	77.36
6	Enhanced performance analysis capabilities	Analysis			60	50	100	100	100	77.27
7	Improved collaboration and communication		Schedule		60	50	100	86	100	72.82
8	Capital cost savings		Budget		100	33	0	86	67	68.23
9	Operating cost savings		Budget		40	67	0	71	67	59.09
10	Improved quality			Product	40	33	0	100	67	59.05
11	Community support			Process	20	17	0	29	67	27.55
12	Improved safety performance			People	20	0	0	43	0	18.23
13	Environmental benefits				0	0	0	14	0	4.45
14	Exchange/resale benefits				0	0	0	0	0	0.00

[1]Domains of sustainability are considered to cover STEEP (Social, Technical, Economic, Environmental and Political) issues respectively in megaproject development and operation. Main domains are provided for each listed benefit of BIM regarding major sustainability issue/s related. [2]Refer to Equation 1 for the calculation method.

consultant group did not report such savings, respondents from the project manager group basically concurred, especially concerning project time, which indicates current uneven savings from adopting BIM in megaproject delivery. In addition to these perceptions of cost and time savings, **Table 9** provides a ranking list of identified benefits of BIM to further summarize respondents' perceptions across megaprojects that they engaged in.

In comparison with the top benefits from BIM cited by contractors in Australia and New Zealand according to the McGraw Hill Construction SmartMarket Report (Bernstein et al., 2014a,b), which highlighted enhancing an organization's image, increased profits, reduced errors and omissions, reduced rework, collaboration with clients/design contractors, and better cost control/predictability, the top five benefits from BIM as ranked in **Table 9** are as follows:

- Data accuracy and consistency, which can reduce errors and omissions as well as rework and so reduce construction cost.
- Design capability, which can enhance an organization's image for not only design contractors but also clients in specific projects.
- Multidisciplinary collaboration, which can improve working effectiveness and efficiency between clients and design contractors.
- Savings of costs and time, which can be achieved throughout construction.

It was noted that these benefits have been consistently identified by leading international practitioners not only within BIM focused events, such as the series of BIM conferences organized by the Institution of Civil Engineers [ICE] (2011–2017) but also in the National BIM Reports published by the National Building Specification [NBS] (2012–2019). Findings from this experimental study on the benefits of BIM for project stakeholders also match the results from recent research by Cao et al. (2016) and Liu et al. (2017) with regard to the adoption of BIM in construction projects.

The recent survey conducted by The Chartered Institute of Building [CIOB] (2016) had 557 respondents from across the construction industry, including 82 respondents who were clients commissioning projects to start in 2016/17 with a total construction value of between £5bn and £10bn. All the identified benefits from adopting BIM in megaproject delivery were than verified in comparison with findings/evidence from three external and independent sources, including

- The survey report by The Chartered Institute of Building [CIOB] (2016),

- The policy document from Australian Institute of Building [AIB] (2013), and
- The practice package from Skanska (2019c).

A summary of this comparison is presented in **Table 10**, in which there is a list of comparative benefits given by the four studies, including this experimental study, in the context of BIM adoption.

This experimental study further made a close observation about what could be learned from such a comparison on BIM benefits in order to verify the result from this experimental study. The Chartered Institute of Building [CIOB] (2016) classified the benefits into six categories, including time, efficiency, collaboration, cost, quality, and the environment, and this category is also used in **Table 10** to make a multiple-source comparison for the purpose of verification. As presented in the table, all of the 14 types of verified benefits within this experimental study can have good matches to those identified by Australian Institute of Building [AIB] (2013) and The Chartered Institute of Building [CIOB] (2016), which are representatives of leading professional bodies, as well as Skanska (2019c), which is representative of global leading construction contractors, within the category of BIM's benefits. According to this comparison, it looks that all BIM-oriented benefits, which were derived and further investigated in this experimental study, have been verified through this multiple source verification process.

BIM and Major Challenges

While it is a matter of fact that there are numerous cases about the underperformed delivery in terms of overruns on cost and time in megaproject development and operation around the world, it has been an emerging task for academic research and professional development to find new advanced technical solutions, which can effectively help the project team tackle major challenges – as described in Section "Major Challenges and Need for Advanced Solutions in Megaproject Delivery" – in megaproject delivery. From this point of view, it is probably a very timely topic to have a further discussion on the adoption of BIM systems in megaproject delivery with regard to whether their verified benefits can be related to confront with the recognized major challenges. This angle to look at the value of BIM could be helpful to identify if it has potentials or actually has worked somewhere to help the project team tackle major challenges in megaproject development and operation no matter how much attention has been given to this initiative, i.e., to incorporate the use of BIM systems to tackle major challenges in megaproject management.

The case study method is further used in this study to identify the relationship between BIM and major challenges through learning lessons from experiences accumulated in megaproject development and operation. Although several megaprojects were considered to make a clear understanding about the connection between BIM and major challenges, one case project particularly chosen for this purpose is the Berlin Brandenburg Airport (BER) project, which has representative features reflecting major challenges and results in megaproject delivery. According to Fiedler and Wendler (2015), five lessons have be learned from the governance of this megaproject in relation to its significant overruns on budget and schedule (Buck, 2017), and these lessons are interpreted below:

- Lesson 1: Project organization. The structures of project governance need to be filled with expertise on all levels and to be working effectively; in the meantime, professional individuals with experiences and skills on all project levels need to be supported by effective governance to reach their potential.
- Lesson 2: Project procurement. It is essential to have a general contractor to work on the client side to engage with project delivery in an all-round professional way.
- Lesson 3: Project planning. There should be sufficient time given to detailed project planning prior to contracts and project execution.
- Lesson 4: Project assurance. There should be accurate and up-to-date information available to support decision making at various managerial levels with regard to functioning assurance with the visibility of project performance.
- Lesson 5: Informed Client. The client needs to be well informed with all relevant resources from both internal and external side of the project.

With regard to the relation between BIM and major challenges in megaproject delivery in the context of these five lessons, a further discussion is give below.

BIM and the Competences of Professional Services

It is an awkward situation in front of the conflict between the pursuit of productivity and the lack of skilled workforce under the demand for lower cost in the construction industry. While the competences of professional services, which are provided by qualified professionals involved at different positions in megaproject development and operation, can be recognized in many current and past megaprojects, it is evidential from the Lesson 1 that it is still a big challenge to achieve the goal of a megaproject on target through competitive professional services, for which both qualified individuals and an effective project organization are essential. An individual observation led by Zigurat (2018) about the problems of the BER project has made it clear that there was a lack of BIM usage in the collaboration among individual architects, electricians and fire safety professionals, and this has strong connections with other four lessons learned from the project. As BIM systems have an inherent capability to well connect professionals by collecting and sharing constant accurate data and information among all megaproject stakeholder groups, the adoption is therefore recommended for the project team to effectively tackle the challenge on professional competences.

BIM and the Overruns of Budget and Schedule

Although it is a persistent problem on the overruns of budget and schedule according to many reports and research into megaproject delivery, there are various causes of the overrun problem among individual megaprojects, and the correlation of overruns between budget and schedule is always evidential.

TABLE 10 | Verification of the benefits from adopting BIM systems.

Category	The Chartered Institute of Building [CIOB] (2016) research into clients' view on BIM		Described experimental study on BIM systems for megaproject stakeholders		Australian Institute of Building [AIB] (2013) Policy on BIM	Skanska (2019c) practice on BIM
	Recognized benefits	**Rate (%)**	**Verified benefits**	**Rank**	**Recognized benefits**	**Recognized benefits**
Time	Saving time in pre-construction design	55	Time savings	5	Saving time on site	Greater certainty for schedule conformance
	Saving time in the construction phase	60				
Efficiencies	Creating efficiencies in hand-over phase	53	Enhanced design capacity	1	Extra coordination checks are largely unnecessary	Enhanced efficiencies
	Creating efficiencies in operation	45	Flexibility and ability to facilitate changes	4	Changes are automatically coordinated across the project	Evaluating options on cost and other project parameters
Collaboration	Promoting collaboration and reduced 'silo' working	63	Multidisciplinary planning and coordination	2	Early identification of problems	Improved communication among project stakeholders
			Accuracy and consistency of data	3	Reducing uncertainty	Reduction of risk
			Enhanced performance analysis capabilities	6	Simulating and analyzing potential impacts	Helping different kinds of quantity calculations of spaces and materials
			Improved collaboration and communication	7	Increasing opportunities for pre-fabrication or pre-assembly off-site	Enhancing the project team's ability to collaborate and use innovative tools
			Community support	11	Product delivery on a just-in-time basis	Helping guarantee design accuracy and completeness
Cost	Saving cost in pre-construction design	55	Capital cost savings	8	Substantial lifecycle cost savings, from design and construction through to maintenance	Cost savings by preventing defects and shortening time on site in using BIM across the whole project.
	Saving cost in the construction phase	54	Operating cost savings	9		Integrating the operation and maintenance
	Having improved margins/fees/profits	40	Exchange/resale benefits	14		Greater certainty for cost conformance
Quality	Promoting safety and regulatory compliance	49	Improved safety performance	12	Improving safety	Improving safety
			Improved quality	10	Information generated is of high quality, and Leading to fewer errors on site	Enabling zero defects to deliver a higher quality product during the construction phase
Environment	Helping cut project's carbon footprint	38	Environmental benefits	13	Minimizing waste on site	Helping sustainability analysis

According to the two case studies on the SCL project in Hong Kong, and the BER project in Germany, it is not identical regarding the adoption of BIM systems can work well to confront the overrun problem, as the SCL project has also encountered the problem of overruns (Chan, 2018) in relation to extreme engineering challenges such as the movement and uneven settlement of the ground in the process of carrying out this large-scale underground works (The Legislative Council Commission [LCC], 2018). In comparison with the BER project in Germany, the five lessons summarized above are also relevant to the SCL project in Hong Kong with regard to the need for a set of comprehensive data and information to be features into BIM systems at an early stage of megaproject delivery. In addition, a further lesson that can be learned from the SCL project, in terms of the incorporation of monitoring the progress of ground movement and settlement, is to constantly update BIM systems with automatic data collection and process (Chen, 2019), for which the integration of sensor systems is one premier technical solution in addition to some others such as simulation (Boateng et al., 2017). Therefore it is probably an objective way to say that the adoption of BIM systems is a necessary but insufficient condition to ensure the project team to effectively confront the problem of overruns in a precise way across interconnected work stages in megaproject delivery.

BIM and the Sustainability of Megaproject

Since the Brundtland Report (United Nations [UN], 1987) was published more than 30 years ago, the construction industry has been experiencing radical innovative changes in an international scale (KPMG, 2019), and it has become a general practice across work stages – from strategic planning through technical design and construction to long-term operation – in all types of building and infrastructure projects to pursue sustainability at both strategic level (Hickman et al., 2015) and tactical level (Forsythe, 2014). For the delivery of megaprojects across industry sectors, megaproject sustainability (Chen, 2018), as a term, has been put forward as a new research theme (Chen and Whitehead, 2016) at the Institution of Civil Engineers (ICE) in London. There have been a number of research into sustainability assessment for megaproject in considering

- Three largest International Hub Airports in China (Chen et al., 2011), the Penang Second Bridge project in Malaysia (Yadollahi et al., 2015), and the Edinburgh Tram Network project in Scotland (Boateng et al., 2015) in the transport sector,
- The Liverpool ONE project or the Paradise project (Chen and Khumpaisal, 2009) in the urban regeneration sector, and
- The Royal Liverpool University Hospital project (Chen et al., 2019) in the healthcare sector, etc.

These research initiatives have all focused on megaproject sustainability in the context of the social environment, the natural environment, and the built environment; and they also dedicated to practice at not only the different project stages on planning, design and construction respectively, but also beyond the project close-out stage (Fahri et al., 2015) within a specific local scope for the longer term operation of the project. While there was little information about megaproject sustainability among the five lessons learned from the BER project, and there is currently a lack of data and information as well as research to substantiate the sustainability of one megaproject in longer term, insights given by professionals including Shennan (2014) have made a strong indicative point about BIM to advance sustainability. From this point of view, BIM is regarded as a technical solution for the project team to confront the challenge on megaproject sustainability so that accumulated data and information can substantiate in longer term.

BIM and its 12 benefits. One outcome from the questionnaire-based survey in this study is a new ranking list of BIM benefits identified across the whole process of megaproject delivery, and this list is shown in **Table 9**. For the top 12 ranked benefits, they were further allocated into a new category in response to the four major challenges discussed above. The new category and its allocated elements are described below:

- Category 1: Competence, which focuses on individual specialisms (capacity and leadership) on analysis, design, and execution (Hart, 2015; Royal Institution of Chartered Surveyors [RICS], 2018; Merrow and Nandurdikar, 2018) respectively in megaproject environment, and holds three ranked benefits.
- Category 2: Overruns, which focuses on the overruns on budget and schedule in megaproject delivery, and holds six ranked benefits equally allocated to cost overrun and time overrun.
- Category 3: Sustainability, which focuses on three essential fundamental elements including people, product, and process (Chen, 2019) in megaproject development and operation across its whole lifecycle, and holds three ranked benefits.

The current review and discussion presented here about the use of BIM to confront major challenges in megaproject delivery are preliminary but evidential and substantiate. Among the top 12 ranked benefits in **Table 9**, the first nine benefits on the ranking list are connected to the two major challenges, i.e., competences and overruns, while the last three benefits are connected to the forth major challenge, i.e., sustainability. This could probably be a meaningful indication regarding a current lack of attention or effort on using BIM systems to achieve megaproject sustainability. It is therefore anticipated that findings on this aspect can be useful for an exploration of new solutions that can facilitate the use of BIM systems to better tackle major challenges in a holistic way within a megaproject environment.

BIM Value Compass

The second experimental outcome is a new tool called BIM Value Compass. The purpose for developing this tool is to visualize the status of BIM adoption with regard to main prioritized benefits over major technical challenges among key megaproject stakeholders. This visualization can provide a holistic overview of how well the current situation could be in terms of using

TABLE 11 | Major challenge oriented scenarios for analyzing prioritized BIM benefits on megaproject.

Major challenges	Prioritized benefits from adopting BIM systems		Scenarios about highly engaged project stakeholders			
	Codes	Benefits	Scenario 1		Scenario 2	
			Stakeholders	*No*	*Stakeholders*	*No*
Professional competence	PB01	Enhanced design capacity	Design Contractor	1	Design Contractor Construction Contractor	2
	PB04	Flexibility and ability to facilitate changes	Design Contractor	1	Design Contractor Construction Contractor	2
	PB06	Enhanced performance analysis capabilities	All parties	6	All parties without Project Manager	5
Cost overruns	PB03	Accuracy and consistency of data	Design Contractor Construction Contractor Project Manager	3	Design Contractor Construction Contractor	2
	PB08	Capital cost savings	Design Contractor Construction Contractor Project Manager	3	Design Contractor Construction Contractor	2
	PB09	Operating cost savings	Facilities Manager	1	Facilities Manager	1
Time overruns	PB02	Multidisciplinary planning and coordination	Design Contractor Construction Contractor Project Manager	3	Design Contractor Construction Contractor	2
	PB05	Time savings	Design Contractor Construction Contractor	2	Design Contractor Construction Contractor	2
	PB07	Improved collaboration and communication	All parties	6	All parties without Project Manager	5
Megaproject sustainability	PB10	Improved quality	Design Contractor Construction Contractor Facilities Manager	3	Design Contractor Construction Contractor Facilities Manager	3
	PB11	Community support	All parties	6	All parties without Project Manager	5
	PB12	Improved safety performance	All parties	6	All parties without Project Manager	5

BIM to confront with major challenges in megaproject delivery. It is therefore expected that the BIM Value Compass can be used to support decision making on relevant adjustments for an enhanced performance against major challenges in megaproject delivery.

The BIM Value Compass consists of 12 cardinal directions in association with the top 12 main benefits, which are on the list presented in **Table 9**, from adopting BIM systems. The reason to have 12 cardinal points for the compass is to equally distribute them within four categories of major challenges. This arrangement is further detailed in **Table 11**, which defines the allocation of individual benefits in four clusters in terms of their relevance/influence to specific technical challenges in megaproject delivery. In addition to this arrangement, **Table 11** also provides two scenarios to which two different sets of stakeholders were deployed with regard to their possible contributions in adopting BIM systems in megaproject delivery. The information about the number of key stakeholders in the two scenarios was then used in a scenario-based experiment to demonstrate how the BIM Value Compass can be used as per its proposed function.

The BIM Value Compass is designed to give each prioritized benefit (PB) a verification of its current or expected status upon BIM adoption at six levels, which represents the number of parties adopting BIM systems among the six main project stakeholders. In this scenario-based experiment, the number of project stakeholders engaging the adoption of BIM systems. Based on scenarios described in **Table 11** and **Figure 4** provides an example of BIM Value Compass, and it demonstrates how the new tool works with a comparison between two scenarios, and the visualization of 12 main prioritized benefits of adopting BIM systems can therefore help to detect the situations of perceived project delivery in terms of the four major challenges and to inform judgments and decision making to improve the performance of megaproject delivery.

The demonstration of BIM Value Compass with regard to its meanings for dealing with the four major technical challenges is further explained below.

Professional Competence

Three PBs were recognized for professional competence to support megaproject delivery against this challenge, and these include

- The enhanced design capacity,
- The flexibility and ability to facilitate changes, and
- The enhanced performance analysis capabilities.

According to the demonstration in **Figure 4**, the scores given to either enhanced design capacity and flexibility or ability to facilitate changes was low as per limited number of engagement among stakeholders, while the score given to enhanced performance analysis capabilities was relatively higher

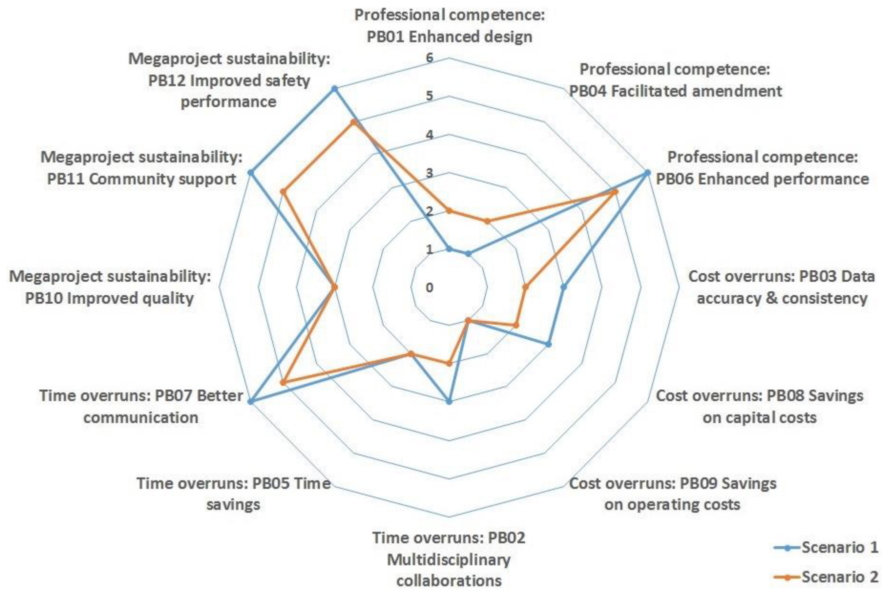

FIGURE 4 | BIM Value Compass for visualizing prioritized benefits among megaproject stakeholders.

as the consequence of more engagement of different stakeholder groups. According to this visualized situation, it is an indication that there are potentials in an expanded engagement of other project stakeholders in addition to Design Contractor to enhance professional competence in megaproject delivery.

Cost Overruns

Three PBs were recognized in relation to cost overruns to support megaproject delivery against this challenge, and these include

- The accuracy and consistency of data,
- The capital cost savings, and
- The operating cost savings.

According to the demonstration in **Figure 4**, the scores given to these three PBs were low as per limited number of engagement among stakeholders. According to this visualized situation, it is an indication that it is necessary for an expanded engagement of other project stakeholders in addition to Design Contractor, Construction Contractor, Project Manager, or Facilities Manager in the pursuit of an effective control on cost overruns in megaproject delivery.

Time Overruns

Three PBs were recognized in relation to time overruns to support megaproject delivery against this challenge, and these include

- The multidisciplinary planning and coordination,
- The time savings, and
- The improved collaboration and communication.

According to the demonstration in **Figure 4**, the scores given to either multidisciplinary planning and coordination or time savings was low as per limited number of engagement among stakeholders, while the score given to improved collaboration and communication was relatively higher as the consequence of more engagement of different stakeholder groups. According to this visualized situation, it is an indication that it is necessary for an expanded engagement of other project stakeholders in addition to Design Contractor, Construction Contractor, or Project Manager in the pursuit of an effective control on time overruns in megaproject delivery.

Megaproject Sustainability

Three PBs were recognized in relation to megaproject sustainability to support megaproject delivery against this challenge, and these include

- The improved quality,
- The community support, and
- The improved safety performance.

According to the demonstration in **Figure 4**, the scores given to improved quality was low as per limited number of engagement among stakeholders, while the score given to both community support and improved safety performance were relative higher as a consequence of more engagement of different stakeholder groups. According to this visualized situation, it is an indication that it is necessary for an expanded engagement of other project stakeholders in addition to Design Contractor, Construction Contractor, or Facilities Manager in the pursuit of sustainability in megaproject delivery.

The scenario-based experiment described here has demonstrated that BIM Value Compass could be a useful tool for megaproject delivery with regard to verifying the current status of BIM adoption and a possible adjustment for an enhanced engagement among the six main stakeholder groups to improve performance against the four major technical challenges.

CONCLUSION AND RECOMMENDATIONS

Experimental Outcomes

This experimental study has identified that variance exists in the level of BIM adoptions across disciplines in megaproject development and operation in Australia, and suggests that the value associated with BIM adoption may also vary among megaproject stakeholders. This scenario has led a completed study that has useful findings, which include a set of verified theoretical hypotheses on BIM adoption, a set of verified BIM benefits, a tool for benefits prioritization to help the project team make the strategy of BIM adoption in megaproject practice, and a tool for benefits verification to help the project team adjust the strategy of BIM adoption in front of major challenges in a megaproject environment. Whilst the sample size was limited and findings may not be suitable to generalize for the whole Australian megaproject sector or at international level, data and information obtained from the questionnaire-based survey were useful in not only testing the six hypotheses, but also identifying and ranking BIM benefits for megaproject stakeholders in Australia. In addition, this experimental study has collected valuable insights from megaproject practitioners upon BIM adoption and major challenges for both qualitative analysis and further research.

Hypotheses on BIM Adoption

Based on an extensive literature review and the authors' perceptions, this experimental study has formulated six hypotheses concerning the value of using BIM systems in megaproject delivery in response to identified major challenges. These BIM oriented hypotheses were established following a thorough consideration of stakeholders' general needs, advanced practices, and major challenges in megaproject development and operation in a generic manner. In addition to ranking BIM's benefits to megaproject stakeholders in Australia, this article provides a summary of these hypotheses at the beginning and then a verification to support the formation of a complete set of theoretical descriptions. The hypothesis verification was conducted through a multiple source verification process based on four sets of information/evidence, and these include a BIM survey by The Chartered Institute of Building [CIOB] (2016), the BIM policy by Australian Institute of Building [AIB] (2013), BIM practices at Skanska (2019c), and an embedded questionnaire-based survey in this experimental study. Findings from the questionnaire-based survey upon the Australian megaproject sector have shown positive support to these hypotheses, as discussed in Section "Hypothesis Verification," while there was also a positive match to megaproject case studies in United States and China. This study on hypotheses verification described in this article indicates that it is a worthwhile attempt to adopt the multiple-source comparison (Legal and General, 2017; Vallée-Tourangeau, 2018), which can not only redeem the weakness of limited sample size and/or dependable feedback in a questionnaire-based survey, but also determine consensus viewpoints from more professionals.

Contributions

This article describes an exploratory research into the value of BIM adoption among megaproject stakeholders to confront major challenges in a collaborative way. It is a unique academic investigation without precedent for lifecycle value oriented BIM adoption in megaproject delivery. Through a pilot study on megaproject delivery in Australia and a number of case studies across the world, this experimental study has collected valuable data and information from experienced professionals working on various disciplines in the megaproject sector to form an initial research report described in this article. It has yielded a set of generic BIM oriented hypotheses following a dedicated literature review which were tested through a questionnaire-based survey, together with a list of ranked benefits that BIM can bring to stakeholders to confront major challenges in megaproject development and operation. These hypotheses have been further examined through multiple-source comparisons with BIM policy by Australian Institute of Building [AIB] (2013), BIM survey by The Chartered Institute of Building [CIOB] (2016), and BIM practices at Skanska (2019c) for its generalization. The benefits prioritization method and the BIM Value Compass put forward from this experimental study can be useful for benefits management in megaproject delivery. Therefore, findings from this experimental study can inform both practitioners and researchers in the context of adopting BIM systems to deal with major challenges in the megaproject environment. In addition, the research has identified some issues in the field of BIM and megaproject management for further research, and these include major challenges and technical solutions. With regard to the management of date and information flow in delivering megaproject (Bishop and Gembey, 1985) and the huge benefits and unprecedented potentials that BIM can bring throughout megaproject lifecycle, this study also had an initial look at revolutionary technical advance in BIM adoption for megaproject delivery, and provides a stepping stone for further research and development. With regard to the adoption of BIM within the project society (Lundin et al., 2015), this research also made an attempt to establish an entire view to inform further research.

Limitations

In addition to the relatively small simple size in the questionnaire-based survey, there are some other limitations in this experimental study. For example, there was only one response received from an individual working at the construction contractor group and none from the facilities management group; therefore a genuine assessment and hypothesis verification of the value of BIM to these groups could not be fully conducted through using data collected from the survey. Furthermore, data relating to the experience levels of BIM usage by designers was not sufficiently varied to allow further hypothesis verification in this study. With regard to the four major challenges in megaproject delivery, this experimental study did not go further in identifying the current status of integrating BIM with project risk analysis methods (British Standards Institution [BSI], 2010) such as environmental risk assessment (REA), multi-criteria decision analysis (MCDA), and structured What If technique (SWIFT), despite that an assumption could be made upon a lack of such initiative in current practice, including benefits management (Infrastructure and Projects Authority [IPA], 2017; Association for Project Management [APM], 2019; Department of Finance [DoF], 2019a) toward well or systematically coordinated BIM adoption in megaproject delivery.

Further Research

This experimental study has addressed several technical points, which could be useful for further research in the field of BIM adoption in megaproject delivery. In response to the research limitations, further research in relation to construction contractors and facilities managers is necessary, ideally through eliciting a larger number of responses in order to obtain trends that are representative of the whole megaproject population. For the questionnaire-based survey, broadening the inclusion criteria for respondents may result in a greater number of responses in future studies, while data to be collected across more geographical locations would also be beneficial. The shortage of responses seen in this study illustrates a possible fact in terms of how the concept of BIM and its applications in Australia, and probably globally, was still in its infancy, and research has shown that inexperience may in fact breed inexperience or less effective usages (Holzer, 2011; Ford, 2018), especially for its integration with megaproject management practice in the context of benefits management as well as risk management (identification, analysis, and control) against the four major challenges. Broadening the scope geographically may provide valuable information to support decision-makers in Australia in relation to BIM adoption for future projects, likely increasing the level of BIM adoption in the country in the future. Furthermore, whilst this study did obtain data in relation to project tender prices, it did not do an analysis of the value of BIM in comparison against the figure. Such research would be valuable in determining at what point the investment required to implement BIM can become profitable with regard to the ROI, at either individual stages or the whole lifecycle of megaproject for various stakeholders; and a preliminary one could be learned from PricewaterhouseCoopers [PwC] (2018).

Postscript

It is at the time of global coronavirus outbreak when this article was finalising in 2020. Whilst social distancing measures are widely implemented to reduce virus transmission, the safe and healthful workplace is on the top priorities to protect workers (Occupational Safety and Health Administration [OSHA], 2020), who continuously provide critical services in hazardous environments, and it has become essential to ensure dependable clean and hygienic workplaces in regard to good respiratory hygiene as highlighted by World Health Organization [WHO] (2020) and effective and efficient protective measures by incorporating new knowledge and lessons learned from the latest scientific research (Moriarty et al., 2020; van Doremalen et al., 2020) and the best practices (Center for Active Design [CAD], 2020; Construction Leadership Council [CLC], 2020). It also becomes important to determine how workplace hygiene and safety can be well integrated into a project lifecycle oriented work procedure such as the Plan of Work by Royal Institute of British Architects [RIBA] (2020) in not only the immediate but also a prolonged time period. In the megaproject sector, major companies such as Arup (Kenny, 2020), Atkins (Robinson, 2020), Lendlease (2020) (Plimmer and Pickard, 2020), Mace Group (Reynolds, 2020), Mitie (2020), and WSP (2020), etc. all have responsive measures for business continuity and, in the meantime, to ensure workforce protection from the threat of coronavirus. In the context of adopting BIM systems by major companies in megaproject delivery, Rubenstone (2020) describes the situation that cloud infrastructure can keep firms afloat from coronavirus strikes and this reflects the prioritised benefit PB07 (Improved collaboration and communication) (see **Table 11**). In addition to the prioritised benefit PB12 (Improved safety performance) (see **Table 11**), the initiative on the adoption of digital twins (Starkov, 2020) to help fight the gigantic threat against safety and wellness is leading a technical way forward, and an extension to workplace safety and/or occupancy safety in normal, exceptional, and extreme circumstances needs to be further determined in the use of BIM systems, This is the lesson being learned from this global coronavirus outbreak.

ETHICS STATEMENT

This study was approved by an Ethics Committee at Heriot-Watt University in UK, where the questionnaire-based survey was conducted. All survey participants were well informed about the study and have given their permissions on data collection and usage.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fbuil.2020.00026/full#supplementary-material

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

GLOSSARY

The following technical terms are used in this article.

Benefits Management

This term refers to a management approach to defining, identifying, planning, tracking, measuring, adjusting and reviewing projected benefits (Infrastructure and Projects Authority [IPA], 2017; Association for Project Management [APM], 2019; Department of Finance [DoF], 2019a).

Benefits Prioritization

This term refers to a technical approach to prioritizing identified benefits under consideration in this article.

BIM Systems

This term is used in this article to refer various systems that are developed and used for building information modeling or management across work stages in construction project.

CMBOK

This acronym stands for the construction management body of knowledge. It refers to a set of structured descriptions about professional knowledge and underpinned techniques to sustain dependable quality services of construction management at both macro and micro scale in the built environment. Please refer to article *Grand Challenges in Construction Management*, which was published at *Frontiers in Built Environment* (5:31. DOI: 10.3389/fbuil.2019.00031), for details about a preliminary framework of CMBOK.

Major Challenges (in Megaproject Delivery)

This article here focuses on four technical challenges that have been identified through research and practices, and these challenges include professional competence, cost overruns, time overruns and substantial sustainability. Please refer to Section "Major Challenges and Need for Advanced Solutions in Megaproject Delivery" of this article for a detailed explanation.

Megaproject

This term refers to a large-scale capital project typically costing more than USD1bn.

Megaproject Delivery

This term refers to the whole process to provide multidisciplinary professional services across various work stages throughout the lifecycle of megaproject. It covers all relevant acts in association with the use of resources in megaproject development and operation as well as the dynamic social and natural environment in a local area.

Megaproject Sustainability

This term refers to the quality of a megaproject with regard to the use of resources and the functions of its services in relation to social, technical, economic, environmental and political (STEEP) aspects/issues across all lifecycle work stages in both short and longer term. The need for substantiating sustainability in megaproject development and operation can focus on people, product, and process in the context of STEEP issues.

Multiple Source Verification

This term refers to a qualitative and/or quantitative approach to validation through checking and comparing targeted issue/s by using evidence collected from several independent sources in the same subject area.