Construction Innovation

Building information modelling (BIM) capability and delivery success on construction projects

Abdul-Majeed Mahamadu, Lamine Mahdjoubi, Colin Booth, Patrick Manu, Emmanuel Manu,

Article information:

To cite this document:
Abdul-Majeed Mahamadu, Lamine Mahdjoubi, Colin Booth, Patrick Manu, Emmanuel Manu, (2019) "Building information modelling (BIM) capability and delivery success on construction projects", Construction Innovation, https://doi.org/10.1108/CI-03-2018-0016
Permanent link to this document:
https://doi.org/10.1108/CI-03-2018-0016

Building information modelling (BIM) capability and delivery success on construction projects

Abdul-Majeed Mahamadu, Lamine Mahdjoubi, Colin Booth and Patrick Manu
Department of Architecture and the Built Environment, University of the West of England, Bristol, UK, and
Emmanuel Manu
School of Architecture Design and the Built Environment, Nottingham Trent University, Nottingham, UK

Received 9 March 2018
Revised 23 June 2018
22 August 2018
Accepted 30 November 2018

Abstract

Purpose – In spite of emerging research on building information modelling (BIM) capability assessment, there is a general dearth of knowledge about the links between often pre-emptive capability measurement attributes and actual delivery success. More so, current studies have not considered success from the wider construction supply chain (CSC) perspective. So far, the perceived importance of capability metrics is not based on post-project evaluations of their contribution to BIM delivery success. This paper aims to identify relevant BIM capability attributes used for qualifying CSC organisations for projects and further aims to investigate their relative importance and influence on some key aspects of BIM delivery success.

Design/methodology/approach – Based on heretofore validated set of BIM capability attributes from semi-structured interviews and a Delphi study, a survey of CSC firms on BIM-enabled projects was used to model the influence of BIM capability attributes on BIM delivery success. Multiple regression modelling was performed to ascertain the nature of the relationship between BIM capability attributes and the key aspects of BIM delivery success as identified from the literature.

Findings – BIM staff experience and the suitability of proposed methodology prior to project commencement were identified as the most influential on BIM delivery quality, as well as delivery within schedule and on budget. Conversely, the administrative and strategic-level capacities were found as the most influential in leveraging collaboration, coordination or integration of the CSC on projects through BIM.

Originality/value – This study provides a step change in prioritising BIM capability criteria based on evidence of their contribution to delivery success in key performance areas, rather than their perceived importance as capability metrics as widely practised.

Keywords Delivery, Performance, Building information modelling (BIM), Construction supply chain (CSC), Projects, Success

Paper type Research paper

Introduction

Building information modelling (BIM) has become a pre-requisite on many construction projects and is expected to eliminate information-flow inefficiencies through virtual collaborative technologies (Arayici *et al.*, 2011). The construction supply chain (CSC) is expected to evolve in terms of the capacity and competencies in BIM-based processes and technology use to succeed in the delivery of projects. In spite of the emergence of several frameworks for measuring BIM capability, it remains unclear which capability attributes are most relevant and responsible for successful delivery of BIM (Succar *et al.*, 2012). In this

Construction Innovation
© Emerald Publishing Limited
1471-4175
DOI 10.1108/CI-03-2018-0016

study, "capability attribute" is used to describe criteria that denote the maturity and capacity to deliver BIM tasks competently and successfully. The assessment of BIM capability has often been pre-emptive with a general lack of empirical justification for selection of relevant capability criteria or attributes (Kam *et al.*, 2013b, 2014; Smits *et al.*, 2016). However, given an increase in the number of projects using BIM over the past decade (BIS 2013a; NBS, 2016), there is sufficient basis for examining the influence of the most widely used BIM capability-measurement attributes on successful delivery of BIM. Furthermore, the success criteria examined must include important CSC performance resulting from BIM use on construction projects. This will enable the identification of potential differences and peculiarities across different CSC organisational and project profiles. In summary, several different criteria have been promoted for use in evidencing the ability to deliver BIM in existing studies. None of these studies have, however, specifically looked at the influence of the proposed criteria on actual BIM delivery success of projects to aid more informed prioritisation of capability attributes during assessments.

To address the identified gaps, the most critical capability attributes being used to assess the BIM capability of firms were identified and prioritised. The prioritisation was based on the attributes' perceived contribution to the successful delivery of BIM with specific focus on supply chain success through BIM as well as BIM delivery quality, within schedule and cost. The assessment is based on the impact of these attributes on specific BIM delivery success areas identified from the literature and relating specifically to the CSC context of BIM use. In the following sections, a review of literature relating to BIM capability and delivery success is first presented. The research methodology applied in the study is then outlined. Subsequent to this, the research findings, their discussion and concluding remarks are presented.

Building information modelling capability and building information modelling delivery success

According to Holt (1998) and Doloi (2009), the main premise on which an organisation should be selected for projects must be their likelihood to succeed or meet the project objectives. Thus, any efforts towards assessing BIM capability of a CSC organisation (for project pre-qualification or selection) must be premised on an understanding of the actual influence of the capability attributes measured on the likelihood of success (Mahamadu *et al.*, 2017). Project success is generally described as attainment or exceeding of project objectives (Takim and Akintoye, 2002). While some studies have explored the role of BIM maturity in project performance generally (Smits *et al.*, 2016), there remain no studies specifically looking at BIM delivery success, especially in the CSC context. Emerging standards, frameworks and tools provide a basis for identifying appropriate BIM capability or qualification criteria for selecting CSC organisations on BIM-enabled projects (Succar, 2009; van Berlo *et al.*, 2012; NIBS, 2012; CIC, 2013a; Kam *et al.*, 2013a, 2013b; Succar *et al.*, 2013; Du *et al.*, 2014; Giel and Issa, 2014; Azzouz and Hill, 2017). However, none of these initiatives provide relevant details about the influence of the BIM utilisation capacity measures on delivery success.

Capability criteria and success

Doloi (2009) used multiple regression analysis to investigate the impact of 43 contractor capability criteria on project success. From the findings, technical expertise, past success, time in business, work methods and working capital emerged as the most influential on contractor's delivery success on a project. Arslan *et al.* (2008) proposed that capability criteria must be categorised based on their contribution to the attainment of quality, cost and time. Al-Zahrani and Emsley (2013) studied the impact of construction qualification-related attributes on the success of completed projects. Based on logistic regression analysis, adequacy of labour ($\beta = 1.284$) emerged as the most influential on delivery on schedule and budget, while the size of the past project completed ($\beta = 0.893$) was the most influential on delivery of quality on projects. Understandably, most construction pre-qualification and selection studies predate the recent mandates for BIM use in many countries; thus, criteria considered in such studies do not include BIM capability or BIM delivery success, more so, not in the CSC context (Mahamadu *et al.*, 2017). Recently, Smits *et al.* (2016) surveyed organisations in The Netherlands to identify the influence of BIM maturity elements on project performance. The maturity elements investigated in this study were strategy, BIM uses, process, information, infrastructure and personnel. Except for strategic-level maturity attributes, which marginally predicted time, cost and quality performance of projects, this study found no statistically significant associations between BIM maturity and project success (time and cost). The findings were also inconclusive about the effect of BIM maturity on delivery of project quality. As a result, Smits *et al.* (2016) cautioned against over-optimism in the expectations that BIM will improve project performance and success overall. Abdirad (2017) also reviewed existing approaches, metrics and criteria used for assessing BIM implementation and revealed the lack of studies examining the role of BIM maturity in the attainment of delivery success. Mom *et al.* (2014) and Tsai *et al.* (2014) identified the following critical success factors of BIM implementation, including organisational strategy; leadership; readiness; capabilities and resources; BIM application; BIM tools; BIM business model; and BIM processes. These studies did not, however, distinguish between success factors and maturity elements. More recently, Antwi-Afaria *et al.* (2018) performed a longitudinal review of BIM success factors and revealed the need for quality, effectiveness and efficiency in delivery. In spite of the relevance of these studies, the factors investigated related to project success and strategic implementation measures of success rather than success in the delivery of BIM itself or the CSC context of BIM use.

Success factors in building information modelling delivery

A review of BIM benefits and performance assessment literature provides useful pointers to some of the most important indicators of success in the BIM and CSC context. Several studies highlight the applicability of the traditional view of success to BIM delivery. For instance, Mom *et al.* (2011) acknowledged the importance of quality, time and cost in the delivery of BIM value. Smits *et al.* (2016) relied on the *iron triangle* metrics (quality, cost and time) to assess the impact of maturity elements on project success. According to Atkin (1995) and Salmeron (2010), the traditional view of project success (quality, time and cost) is a valid measure of the success of information systems. More specifically, the success of information systems in construction projects should be based on data accuracy, timeliness, control and auditability (Atkin, 1995). Saleh and Alshawi (2005), similarly, relied on timeliness of implementation and cost as a measure of success in the implementation of information systems in the construction industry. Du *et al.* (2014) developed a framework for benchmarking BIM modelling performance with emphasis on quality, time and cost-efficiency related metrics for the BIM modelling process. According to Al-Zahrani and Emsley (2013), the iron triangle remains the most universally applicable success indicator in most construction project scenarios. Consequently, studies examining the successful delivery of information systems (Atkin, 1995) and BIM, more specifically (Du *et al.*, 2014; Abdirad, 2017) in construction, have adopted the "iron triangle" for definition of success. As outlined in Table I, key dimensions of success were adopted relative to the "iron triangle", based on a review of BIM studies.

In addition to the iron triangle view of success, the other important dimensions reviewed were performance issues related to the integration of project supply chain through BIM. To

Table I.
Review of BIM delivery success factors for CSC

BIM delivery success	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Success variable description
	References*														
BIM modelling success															
Quality				X		X	X	X	X	X				X	Overall conformance to technical requirements (i.e. client or project and specifications [including accuracy, usability of data or BIM models])
Schedule (timeliness)				X		X	X	X	X	X				X	Attainment of BIM deliverables within time (i.e. as set out in project programmes, data drop agreements or master information delivery plans MIDP)
Budget (cost/economy)						X	X	X						X	Attainment of BIM deliverables within budget
Supply chain success through BIM															
Collaboration	X	X	X		X	X					X	X	X	X	Trust-based relationship and commitment for the attainment of common business objectives through transparent and effective communication
Coordination	X	X	X	X	X	X					X	X	X	X	Effective operations and resource alignment and control for the attainment of project objectives through communication, transparent and effective project data management
Integration	X	X	X		X						X	X	X		Functional coupling of fragmented CSC organisations into an integrated project delivery team(s)

Notes: *References: A = Pryke (2009); B = Lonngren *et al.* (2010); C = Vrijhoef (2011); D = Kam *et al.* (2012); E = BIS (2013b); F = CIC (2013a); G = Keavney *et al.* (2013); H = Du *et al.* (2014); I = Mom *et al.* (2014); J = Tsai *et al.* (2014); K= Khalfan *et al.* (2015); L = Papadonikolaki *et al.* (2015a); M = Papadonikolaki *et al.* (2016); and N = Abdirad, (2017)

identify these dimensions of BIM delivery success, the role of the CSC was examined, revealing four important dimensions: creating a focus on the CSC rather than a single organisation; creating an effective interface between SCM principles and the construction site; transferring activities from construction sites to the CSC; and focussing on the integrated management of the CSC (Khalfan *et al.*, 2015). Vrijhoef (2011) and Papadonikolaki *et al.* (2015a) highlight the importance of collaboration, integration and coordination to CSC success, as well as the role of BIM, in achieving these performance objectives. The benefits of the pervasive nature of BIM include transparency and communication, which further enhance collaboration in CSC (Papadonikolaki *et al.*, 2015a). From a review of policy documents (BIS, 2011; 2013a,b) and other literature (Pryke, 2009; Lonngren *et al.*2010; Vrijhoef, 2011), three distinctive success areas are apparent:

Collaboration

The CSC often consists of a temporary setup for one-off projects, resulting in instability and fragmentation (Dainty *et al.*, 2001). The levels of fragmentation can be reduced through open and honest communication that is facilitated by integrated BIM project environments (Vrijhoef, 2011).

Coordination

CSC is functionally characterised by fragmentation that prevents effective convergence of materials, goods and services on site efficiently (Manu, 2014). Thus, cross-functional coordination is vital to achieving this with BIM-based communications regarded as central to enhanced operational planning through visualisation and virtual prototyping (Vrijhoef, 2011).

Integration

The CSC is also characterised by structural fragmentation. BIM, however, enables seamless organisational structures with the aid of technology (Papadonikolaki *et al.*, 2015a, 2015b). Thus, BIM-based centralised communication enables the disparate organisations to work better as a single unit (Vrijhoef, 2011). Based on the review of literature, the success indicators adopted for this study are summarised in Table I.

Building information modelling capability criteria used in existing assessment tools and frameworks

Succar *et al.*'s (2012) BIM competency framework provides a generic description of BIM capability attributes, namely, technology, process and policy. Technology attributes represent organisational attributes related to physical artefacts, while process category represents resources-, activities-, workflows-, products-, services-, leadership- and management-related attributes, often used to evidence BIM utilisation capacity (Succar, 2010). Policy attributes refer to contracts, benchmarks and guidance for BIM implementation within organisational units (Succar *et al.*, 2012). Dib *et al.* (2012) categorised capability attributes as follows: planning and management of process and technology; team structure; hardware; process definition; and information management abilities. The Pennsylvania State University BIM guide (CIC, 2013a), on the other hand, relies on the following distinctive areas of BIM capability: strategy; BIM uses; process; information; infrastructure; and personnel. Different criteria have been promoted for use in evidencing the ability to deliver BIM. None of these studies have, however, specifically looked at the influence of the proposed criteria on actual BIM delivery success on projects to aid more informed prioritisation of capability attributes during assessments. Overall, these studies have focussed more on the aspects of BIM that give an indication of the extent of BIM maturity achieved by an organisation but do not provide empirical basis for BIM delivery success on projects. BIM delivery success on projects might arguably require more than just achieving a state of maturity based on technology, processes and policy, as from the CSC perspective, these have to be mobilised together to achieve the collaboration, integration and coordination requirements which are perhaps more predictive of BIM delivery success on projects, especially with regard to CSC objectives. Thus, this study aims to bridge this gap through an empirical enquiry of the influence of BIM capability on BIM delivery success.

Research methodology

Based on a pragmatic philosophical position, the influence of 28 BIM capability criteria on BIM delivery success indicators, was modelled based after a survey of BIM enabled projects (n = 64). The 28 BIM capability criteria have been previously validated in Mahamadu *et al.* (2017). The 28 BIM capability criteria were validated through interviews with BIM experts (n = 8) and a two-round Delphi study (n = 25 [round 1] and n = 30 [round 2]) of experienced BIM practitioners in Phase 1 of the study, which has been reported in Mahamadu *et al.* (2017), as presented in Table II.

Phase 1 (interviews and Delphi study)

Semi-structured interviews were conducted with BIM experts to explore relevant BIM capabilities, given the relative novelty of BIM capability as a subject. This was to solicit their expert opinion about BIM capability attributes that are currently being used in practice to consolidate the list of attributes identified from literature. Phenomenological principles were relied on to satisfy the requirements of the qualitative parts of the study. This is as a result of the need to investigate construction experts' personal perspectives on BIM capability criteria based on their experience of working on construction projects. Similar methods have been applied in the exploratory phase of mixed method research (Manu, 2012). Furthermore, according to Adriaanse (2007) and Navendren *et al.* (2014), digital technology research in construction requires such initial qualitative explorations owing to its novelty to provide sufficient context for further investigations. Interviewees comprised BIM managers, digital engineers, commercial managers and quantity surveyors with extensive industry and BIM experience. All interviewees had management roles in the BIM implementation of major construction projects and organisations. Interviews were transcribed verbatim for analysis. The interviews, which lasted up to 40 min on average, represented the exploratory phase of the mixed method research strategy adopted. Interviews were terminated after the eighth session as a result of saturation, as suggested by Guest *et al.* (2006).

After the identification of BIM capability attributes, a Delphi survey was used to establish the most relevant attributes. The Delphi technique was first developed by Dalkey and Helmer (1963) as a method for achieving convergence of opinion among groups of experts. Delphi has gained popularity within construction-management studies recently and is regarded as a strong approach for the determination of capability or competence criteria (Hallowell and Gambatese, 2010). Delphi has been adopted for contractor selection criteria (Hatush and Skitmore, 1997), as well as BIM competence criteria prioritisation for owner organisations (Giel and Issa, 2014). The Delphi survey of 30 construction practitioners resulted in 25 valid final Delphi round responses. This phase was used to validate the list of capability attributes generated from the interviews and literature, as well as to reduce it to a concise number consisting of only the most critical attributes being used within the industry for evidencing the BIM capability of CSCs.

Phase 2 (survey)

A survey was then used to solicit senior project participant's independent evaluation of the BIM delivery performance of a CSC firm on a project, as well as to evaluate the extent of their BIM capability and its influence on the success indicators investigated (Table I). According to Yin (2003), surveys are appropriate for the exploration of relationships between personal or perception-based variables on samples wider than those covered by qualitative strategies. A survey research strategy was therefore adopted to enable investigation of research propositions from the earlier phases among a wider group of respondents (i.e. projects). Surveys are the most associated strategy with the conduct of

Table II. Critical BIM capability attributes and review of relevant frameworks

Critical BIM capability attribute		Interview	A	B	C	D	E	Delphi validation
			Literature-relevant BIM capability frameworks*					
Competence								
Professional and academic qualifications	Key technical staff BIM qualification	X	O	X	X	O	O	√
	BIM staff availability for project	X	O	X	O	X	–	√
	Organisation's BIM accreditations and certifications	X	X	O	X	O	X	√
	Organisation's BIM training arrangements	X	X	X	X	X	X	√
Staff experience	Managerial staff BIM experience	X	X	X	O	O	X	√
	Key technical staff BIM experience	X	X	X	X	X	X	√
Organisation experience	BIM software experience	X	X	X	X	X	X	√
	Past BIM project experience	X	O	O	O	X	O	√
	BIM experience on similar project	X	O	O	O	X	O	√
	Internal use of collaborative IT Systems	X	X	X	O	O	X	√
Capacity and resources								
Administrative and strategic capacity	IT vision and mission	X	O	X	O	X	O	√
	Quality of BIM implementation strategy	X	X	X	X	X	X	√
	BIM research and development	X	X	X	X	O	X	√
Technical (physical) resources	Software availability	X	X	x	X	X	X	√
	Data storage (suitability and capacity)	X	X	x	O	O	X	√
	Network infrastructure availability	X	X	X	X	O	X	√
Specific BIM modelling capacity	BIM standards	X	X	X	X	X	X	√
	Data classification and naming practices	X	X	X	O	X	X	√
	Model maturity expertise/capacity	X	X	X	X	X	X	√
	LOD/LOI expertise/capacity	X	X	X	O	X	X	√
Proposed methodology	Suitability: BEPs for project	X	–	X	O	X	O	√
	BIM vendor involvement and support	X	O	O	O	O	–	√
Culture and Attitude								
Reputation	Reputation: performance on past BIM projects	X	–	O	–	O	–	√
Technology readiness	Attitude towards new technology/willingness	X	X	X	O	X	X	√
	Awareness of BIM benefits	X	–	O	O	X	O	√
	Extent of IT support to core business and processes within firm	X	O	X	O	O	O	√
Organisational structure	Organisational structure (level of decentralisation)	X	X	X	X	X	O	√
Cost	Cost/price of BIM service	X	–	–	–	X	–	√

Notes: Interview and literature: (×) = largely considered; (o) = somewhat considered; and (–) = not considered/proposed. *A = Quickscan TNO (Sebastian and van Berlo, 2010); B = VDC scorecard (Kam *et al.*, 2014); C = BIMMI (Succar, 2009); D = University of Pennsylvania CIC (2013a); E = owners competence framework (Giel and Issa, 2014)
Source: Mahamadu *et al.* (2017)

quantitative research, including several BIM studies as well as evaluation of the influence of capability on delivery success (Kam *et al.*, 2014; Smits *et al.*, 2016). The survey consisted of practitioners on BIM-enabled projects (n = 64) and was thus used to establish the influence of the 28 critical BIM capability criteria on various aspects of BIM delivery success in the CSC context. The survey was used to solicit senior project participant's independent evaluation of the BIM delivery performance of a CSC firm on a project, as well as to evaluate the extent of their BIM capability and its influence on the success indicators investigated (Table I).

Data analysis

Phase 1 (interviews and Delphi study)

Thematic analysis was deemed appropriate contextualisation of capability attributes proposed from the interviews and literature (Thomas and Harden, 2008; Navendren *et al.*, 2014). Thematic analysis allows systematic data structuring to adduce patterns relevant to the phenomenon being investigated (Creswell, 2007). Based on the coded responses, interviewees' opinions on BIM capability attributes were further categorised into distinctive but related concepts, leading to the development of a three-tier hierarchy of BIM capability attributes presented in Table II.

The Delphi study was used as a validation of interviews and to develop a more parsimonious list of capability attributes. Critical attributes were determined through statistical determination of consensus with the aid of the interrater agreement (r_{wg}). Based on the analysis of the r_{wg} values and mean ratings, all criteria that recorded acceptable ($r_{wg} \geq$ 0.750), as well as a mean scores equivalent **to** or above "agree", were retained. This was based on the five-point rating scale used in the Delphi survey (1 = strongly disagree, 2 = disagree, 3 = neither agree nor disagree, 4 = agree, 5 = strongly agree). From the principles of mathematical approximation, BIM qualification criteria with mean values $\geq$3.5 were accepted as critical, provided there was consensus among participants (i.e. $r_{wg} \geq 0.750$). Delphi studies involve iterative rounds of data collection, which is terminated when there is stability or insignificant changes in responses between rounds. Spearman's correlation test coefficient (rho) was adopted to assess stability between Delphi rounds, considering the ordinal nature of the data gathered from the questionnaires (Field, 2013). The correlations tests between Delphi rounds resulted in statistically significant correlations. Hence, there was no significant shift in participant opinion, which further led to reliance on data from round two of the process.

Phase 2 (survey)

Both descriptive and multivariate analyses were used to explore the data. Descriptive statistics are often used to uncover the patterns, distribution and simple deviations within sample data (Denscombe, 2010). Measures of central tendency (means) were used to identify response points on the questionnaire scales (Denscombe, 2010). Standard deviation (SD) was used to assess the measure of spread within data. Multivariate statistical modelling techniques were then used to model the relationship between the BIM capability attributes and key BIM delivery success indicators in the CSC context. This was achieved through multiple linear regression (MLR) analysis of survey data. This process involved the construction of an index of BIM capability attributes and success variables. Thus, an index of the 11 main BIM capability attributes (consisting constituent 28 capability attributes) were modelled as independent variables on success indicators representing the dependent variables. Two dimensions of success indicators were drawn from the literature (Table I). The first dimension was "BIM modelling success" representing the traditional *iron triangle* view of success. This dimension of success consisted of criteria measuring the quality of BIM, delivery of BIM on schedule (time) and delivery of

BIM within budget (cost). The second dimension was "CSC success through BIM" representing the attainment of strategic CSC/SCM objectives through the application of BIM, namely, collaboration, coordination and integration. This study relied on modelling several observational measures and latent variables from a survey, thus making MLR and structural equation modelling (SEM) the most suitable analysis techniques (Field, 2013; Hair *et al.*, 2010). The choice of MRL over SEM was because of a couple of reasons. SEM is more suitable where there is very complex relationships between variables; however, the relationships examined in this study were less complex, thus making MLR adequate (Anvuur, 2008). Furthermore, SEM is recommended to overcomes problems associated with MLR analysis where there is prevalence of issues such as multicollinearity and spurious suppression (Field, 2013; Hair *et al.*, 2010). None of these were, however, observed from preliminary analysis of data to determine non-violation of primary assumptions of MLR. The key assumptions that had to be met for effective application of MLR were linearity of the relationship between outcome and predictor variables; constant variance of the error terms; independence of the error terms; and normality of the error term distribution. All these were met after examination of residuals from the MLR and test of normality of variables used. Another key factor which made SEM undesirable was the fact that it often requires large cases of data for effectiveness (i.e. more than 300) (Anvuur, 2008). Thus, MLR was the most suitable statistical modelling technique for the data set in this study. The choice of MLR was also consistent with the principle that simple and minimally sufficient statistical analysis are most appropriate to avoid over-interpretation (Best and Smith, 2005).

Pearson's correlation coefficient (r) was also used to establish linear relationships between variables to check intra-variable relationships as a precursor to the MLR analysis (Field, 2013). A parametric test (r) was chosen, given each variable studied was a composite variable developed from an index of several variables. Thus the variables assumed a normal distribution making a parametric test the most suitable. Based on classical MLR modelling, the relationship between the predicted outcomes Y_p and predictor variables (X_1, X_2, X_{k-1}, X_k) was assessed. The MLR was used for the development of predictive models for BIM delivery success through BIM capability attributes (as the predictor variables). The stepwise method in MLR was adopted in this study to support development of optimum regression models containing only the most relevant predictors after iterative rounds of analysis (Brace *et al.*, 2003).

The capability criteria adopted in survey. Table II presents a summary of the 28 critical BIM capability attributes adopted from literature and interviews and subsequently validated by the Delphi survey (Mahamadu *et al.*, 2017). These BIM capability attributes are most suitable for the study of influencers of success, given they incorporate all attributes relied on in BIM project pre-qualification and selection, thereby providing a wide range of criteria as well as opportunities for understanding the relative importance of the criteria for selecting firms most likely to succeed prior to project commencement.

Recruitment and sampling

As cited by Denscombe (2010), decisions on selecting research participants can be as precise when based on familiarity and good judgment. Preliminary enquiries about major BIM-enabled projects was performed through internet searches, published case studies and industry event discussions. Interview and Delphi experts were subsequently recruited with the total number of subjects commensurate with past qualitative (n = 8) and Delphi studies (n = 25/30) in BIM literature (Navendren *et al.*, 2014; Giel and Issa, 2014). Similar methods were used to identify expert and experienced BIM professional respondents working on BIM projects, who were targeted through for random distribution of surveys both online and in paper versions. To determine a suitable sample size, the Creative Research Systems (2003) formula was applied leading to a recommended sample size of 480. This led to the posting of the online version of surveys to identifiable internet groups with construction professionals and in institutions that use BIM. This included LinkedIn, Google and Yahoo groups restricted to various BIM and construction professionals. The LinkedIn professional group pages contacted included "BIM4SME", "RICS", "CIOB", "ICE" "BIM Experts" and "BIM Architects", among others. These groups have memberships ranging from 330 to over 10,000. Furthermore, 160 questionnaires were directly distributed to individuals in the generated contact list from the internet searches and solicitation of contacts from BIM events. The survey resulted in 13.3 per cent (n = 64) response rate, which is acceptable based on a review of similar construction-management studies (Ankrah, 2007).

Results

The survey was used to ascertain the perceived influence of the 28 critical BIM capability attributes (Table II) on the six dimensions of success reviewed (Table I). The majority of survey respondents were BIM managers or technicians (31.4 per cent), with a substantial proportion possessing between 11 and 15 years of industry experience (46.7 per cent) or 4-6 years of BIM or other virtual digital construction technologies experience (35.9 per cent). In relation to academic qualifications, 42.2 per cent of respondents were holders of a bachelor's degree as their highest qualification with a good number of post-graduate degree holders (masters: 29.7 per cent and doctorate: 7.8 per cent). This is indicative of a substantially experienced and knowledgeable group of respondents.

In relation to the background of the projects assessed, 19.3 per cent were large-scale with estimated project values above £50m. Though the majority of projects (80.7 per cent) were less than £50m in value, more than half were above £25m. Most of the projects surveyed reported middle-tier CSC involvement in their BIM implementation or strategy, though a much less proportion (1.6 per cent) reported lower-tier CSC involvement in BIM processes. The projects assessed in the survey were mostly building projects (90.3 per cent), as summarised in Table III.

Modelling the impact of building information modelling capability attributes on delivery success

Staff experience (mean = 3.883) emerged as the most important attribute, with a positive influence on overall BIM delivery success. The other important influencing attributes were *specific BIM modelling capacity* (mean = 3.426), *organisation's experience* (mean = 3.399) and *technology readiness* (mean = 3.354). The constituent attributes regarded as most highly influential on BIM delivery success were: *technical staff BIM experience, suitability of proposed BIM execution plans for project (BEPs), awareness of BIM benefits, organisation's BIM training arrangements*, *managerial staff BIM experience*, *key BIM software experience* and *past BIM project experience*. The rest were *quality of BIM implementation strategy*, *software availability, BIM standards*, *data classification and naming practices* and *level of detail/information (LOD/LOI) capacity*. The remaining attributes had arithmetic means between 1.5 and 2.5, representing "Slightly Influential" on the scales. These were *BIM vendor involvement and support* and *reputation* (*in relation to performance on past BIM projects*) of CSC organisation. In spite of their reported low level of influence, they remain influential with none of the attributes assessed reported as not influential on BIM delivery success on projects. This is summarised in Table IV.

From the analysis, the area within which assessed firms performed best overall was the delivery of BIM within budget (mean = 4.656). This was followed by the delivery quality of

	Frequency	(%)	Cumulative (%)
Project size			
Less than £25m	30	48.4	48.4
£26-50m	20	32.3	80.6
£51-75m	6	9.7	90.3
£76-100m	3	4.8	95.2
Over £100m	3	4.8	100.0
Supply chain involvement in BIM process			
Only top tier	5	8.1	8.1
Some middle tier	38	61.3	69.4
Significant middle tier	18	29.0	98.4
Lower tier	1	1.6	100.0
Project type			
Civil	6	9.7	9.7
Building	56	90.3	100.0

Table III. Background of surveyed projects

BIM (mean = 4.297), delivery within schedule (mean = 4.094) and use of BIM to achieve collaboration (mean = 3.922) within the project CSC. Respondents were of the opinion that coordination (mean = 3.469) and integration (mean = 3.313) were not attained to similar extents as the other success factors. While the high standard deviations (SD = 0.946 - 1.123) could be indicative of high level of variability in the performance assessment, Cronbach's Alpha (0.810) was indicative of highly reliable scales for assessing success. The results are summarised in Table V.

Association between building information modelling capability attributes and building information modelling delivery success indicators

Based on Pearson's correlation coefficients (r), all capability attributes were found to have a positive association with BIM delivery success overall. *Professional and academic qualifications* recorded the most significant level of association ($r = 0.520$; $p < 0.01$, $n = 64$) with BIM modelling success, while *cost* recorded the least ($r = 0.283$; $p < 0.05$, $n = 64$). Most of the BIM capability attributes were found to influence the delivery of quality in comparison with the rest of the success indicators. *Cost* charged for BIM services was the only attribute that did not record association with quality delivery of BIM ($r = 0.144$; $p > 0.05$, $n = 64$). The capability criteria with the most significant association with quality was *staff experience* ($r = 0.602$; $p < 0.01$, $n = 64$).

A total of five capability attributes were found to have a significant degree of association with the delivery of BIM on schedule with *proposed methodology* ($r = 0.475$; $p < 0.01$, $n = 64$) recording the highest degree of association. Furthermore, seven of the capability attributes recorded significant degrees of associations with the delivery of BIM within budget. *Administrative and strategic capacity* recorded the highest level of association ($r = 0.482$; $p < 0.01$, $n = 64$), followed by *staff experience* ($r = 0.404$; $p < 0.01$, $n = 64$). In relation to the delivery of CSC success through BIM, only four of the capability attributes recorded statistically significant levels of associations, with *administrative and strategic capacity* emerging with the highest degree of association ($r = 0.507$; $p < 0.01$, $n = 64$). *Administrative and strategic capacity* emerged with significant correlations across all three areas of CSC success through BIM ($r = 0.374$; $p < 0.01$, $n = 64$). Coordination through BIM had a weak but

Variables (BIM qualification criteria)	N	Range	Statistics Rank	Mean	SD	Degree of influence* SI	I	VI
Competence								
Professional and academic qualifications (mean = 3.067)								
Key technical staff BIM qualifications	64	4	21	2.938	1.067		√	
BIM staff availability for project	64	4	14	3.344	0.946		√	
Organisation's BIM accreditations and certifications	64	4	28	2.391	1.229	√		
Organisation's BIM training arrangements	64	4	7	3.594	1.065			√
Staff experience (mean = 3.883)								
Managerial staff BIM experience	64	4	10	3.563	1.125			√
Key technical staff BIM experience	64	3	1	4.203	0.858			√
Organisation's experience (mean = 3.399)								
BIM software experience	64	3	5	3.656	0.781			√
Past BIM project experience	64	3	7	3.594	0.921			√
BIM experience on similar project	64	4	19	3.016	1.076		√	
Internal use of collaborative IT	64	4	15	3.328	0.977		√	
Capacity and resources								
Administrative and strategic capacity (mean = 3.333)								
IT vision and mission	64	4	18	3.156	0.979		√	
Quality of BIM implementation Strategy	64	3	7	3.594	0.849			√
BIM R&D	64	4	16	3.250	1.084		√	
Technical (physical) resources (mean = 3.068)								
Software availability	64	4	11	3.500	0.960			√
Data storage	64	4	24	2.828	0.901		√	
Network infrastructure	64	4	23	2.875	0.951		√	
Specific BIM modelling capacity (mean = 3.426)								
BIM standards	64	4	6	3.625	1.266			√
Data classification and naming Practices	64	4	11	3.500	1.039			√
Model maturity capacity	64	4	22	2.891	1.143		√	
LOD/LOI capacity	64	4	4	3.688	1.125			√
Proposed methodology (mean = 3.149)								
Suitability of proposed BIM execution plans for Project	64	3	2	3.844	0.801			√
BIM vendor involvement and support	64	4	26	2.453	1.181	√		
Culture and attitude								
Reputation (mean = 2.453)								
Performance on past BIM projects	64	4	26	2.453	1.181	√		
Technology readiness (mean = 3.354)								
Attitude towards new technology/ willingness	64	4	13	3.359	1.060		√	
Awareness of BIM benefits	64	3	3	3.734	0.802			√
Extent of IT support to core business and processes	64	4	20	2.969	1.098		√	
Organisational structure (mean = 2.781)								
Level of decentralisation	64	4	25	2.781	1.105		√	
Cost (mean = 3.188)								
Price charged for BIM service	64	4	17	3.188	0.906		√	

Notes: *Influence scales: SI (slightly influential) = 2; I (influential) = 3; VI (very influential) = 4. NB: Please note that no mean scores corresponded with NI (not influential at all = 1); and EI (extremely influential = 5), thus, not shown in Table for brevity

Table IV.
Descriptive analysis of influence of BIM capability attributes on overall delivery success

statistically significant correlation coefficient ($r = 0.377$; $p < 0.01$, $n = 64$), while integration through BIM recorded an appreciable correlation ($r = 0.522$; $p < 0.01$, $n = 64$).

Modelling the impact of capability attributes on building information modelling delivery success

Two MLR models were developed to ascertain influence of capability attributes on the two dimensions of delivery success (BIM modelling success and CSC success through BIM). With regard to BIM modelling success, the outcome variable consisted of respondents' assessment of CSC performance in relation to BIM modelling quality, BIM delivery on schedule and BIM delivery within budget on a current or recently completed project. The multiple regression modelling resulted in a statistically significant regression equation (F [2, 61] = 18.629; $p < 0.05$) with an R^2 of 0.379. The adjusted R^2 of 0.359 denotes 35.9 per cent of the variation in the BIM modelling success because of predictor variables. Based on the findings, BIM modelling success can thus be predicted from Equation (1).

Equation (1): regression equation for predicting BIM modelling success:

$$\text{BIM MODELLING SUCCESS} = 0.857 + 0\,.483(\text{Staff Experience}) + 0.447(\text{Proposed Methodology})$$

From this regression equation, BIM delivery success on a project increases per 0.483 unit increments in level of *staff experience* and 0.447 unit increments in the level of suitability in relation *to BIM proposals* submitted by firms prior to commencement of projects. Both *staff experience* ($p < 0.05$, $n = 62$) and *proposed methodology* ($p < 0.05$, $n = 62$) were significant predictors of overall BIM modelling success, as summarised in Table VI and Figure 1.

The Durbin–Watson test recorded value of 1.383, indicative of no independence of the error term. The variance inflation factor (VIF) was within the acceptable range (1.179 for

Variables	Statistics N	Range	Min	Max	Mean	SD	Extent of attainment on project Fair	Good	Very Good
Budget (cost)	64	4	2	6	4.656	0.946			√
Quality	64	5	1	6	4.297	1.079		√	
Schedule (time)	64	5	1	6	4.094	1.123		√	
Collaboration	64	5	1	6	3.922	1.088		√	
Coordination	64	5	1	6	3.469	1.038	√		
Integration	64	5	1	6	3.313	1.111	√		

Notes: Scales: not at all = 1; poor = 2; fair = 3; good = 4; very good = 5; and excellent = 6

Table V. Level of attainment of BIM delivery success by CSC organisations

	Variables in equation β	Std. error	Beta	t	Sig.	Tolerance	VIF
(Constant)	0.857	0.563		1.521	0.134		
Staff experience	0.483	0.140	0.377	3.441	0.001	0.848	1.179
Proposed methodology	0.447	0.135	0.362	3.301	0.002	0.848	1.179

Notes: Std. error = 0.711; Durbin–Watson = 1.383 ANOVA [F(2,61) = 18.629, p = 0.000]

Table VI. Regression analysis results for BIM modelling success *staff experience* and 1.179 for *proposed methodology)* (Hair *et al.*2010). Further residual analysis revealed no violations of MLR assumptions.

With regard to CSC success through BIM, the outcome variable consisted of ratings of performance outcomes in relation to collaboration, coordination and integration of the CSC through BIM on the projects assessed. The MLR exercise resulted in a significant regression equation ($F\,[1, 62] = 21.489$; $p < 0.05$), with an R^2 of 0.257. Adjusted R^2 was 0.245, implying that the predictors in the regression model accounted for 24.5 per cent of the variation in CSC success through BIM. From the analysis, overall CSC success through BIM can be predicted from Equation (2).

Equation (2): regression equation for predicting CSC success through BIM:

$$\text{OVERALL SUPPLY CHAIN SUCCESS THROUGH BIM} = 1.483 + 0.595(\text{Administrative and Strategic Capacity})$$

From this analysis, administrative and strategy-related capacities are the most significant predictors of performance related to collaboration, coordination and integration of the CSC through BIM. Table VII and Figure 2 are a summary of the key parameters of the regression model for predicting CSC success through BIM.

The Durbin–Watson test for MLR model for CSC success through BIM was 2.059, indicating that the residual errors were not correlated unduly. This is indicative of no evidence of first-order autocorrelation. The VIF of the significant predictors was 1, thus, within acceptable range (Hair *et al.*, 2010). This is indicative of highly satisfactory results in relation to the violation of collinearity assumptions. Further residual analysis revealed no violation of the principle MLR assumptions.

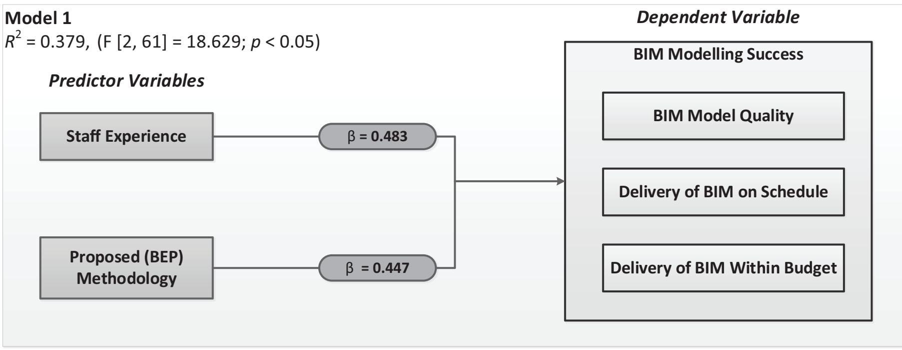

Figure 1. Summary of regression analysis for BIM modelling success

Table VII. Regression results for overall supply chain success through BIM

Variables in equation	β	Std. error	Beta	t	Sig.	Tolerance	VIF
(Constant)	1.483	0.440		3.366	0.001		
Administrative and strategic capacity	0.595	0.128	0.507	4.636	0.000	1.000	1.000

Notes: Std. error = 0.781; Durbin–Watson = 2.059; and ANOVA [$F(1,62) = 13.120$, $p = 0.000$]

Mediating and moderating effect of project and organisational characteristics
Mediation in a regression model refers to the elucidation of the mechanisms that underlies an observed relationship between independent and dependent variables (Kenny, 1986; Hayes, 2009). Mediator variables, thus, clarify the nature of the relationship between the predictors and outcome variables (Kenny, 1986). This is often done through the investigation of the influence of mediating variables in the regression modelling (Hayes, 2009). In this study, mediation analysis was undertaken to identify whether or not project complexity mediated the influence of capability attributes on delivery success. If significant changes occur in the model parameters, this is indicative of a mediating role of the additional variables (project complexity characteristics). The three principal dimensions of complexity measured were project size, BIM complexity and supply chain complexity. Project size was based on the value of the projects surveyed and categorised within the following ranges: < £25m; £26-50m; £51-75m; £76-100m; and > £100m. BIM complexity accounted for BIM task responsibility of the CSC organisation, project BIM model complexity (including BIM maturity level) and product or facility complexity (in terms of design). Supply chain complexity included the level of CSC's involvement in the BIM process and the extent of the use of BIM across the CSC of the project. MLR was re-run with the inclusion of mediator variables, revealing only marginal decrease in the adjusted R^2 from 0.245 to 0.229 with evidence of additional significant predictor, *project supply chain complexity* ($\beta = 0.423$; $p < 0.05$, $n = 62$) for CSC success through BIM. *Administrative and strategic capacity* ($\beta = 0.754$; $p < 0.05$, $n = 62$) remained a strong predictor in spite of an overall drop in the variance accounted for in the entire regression model. No project characteristic was found to influence attainment of BIM modelling success.

Moderation in regression is used to describe the relationship between two variables when they are dependent on a third variable called the moderator (Kenny, 1986). The relationships between the predictors in the regression models for BIM modelling success and CSC success through BIM were tested through a moderation analysis, with the aid of PROCESS software for SPSS (Hayes, 2016). Using a path analysis framework, the PROCESS tool provides a moderation analysis through an estimation of the coefficients of a regression model (Hayes, 2016). None of the project and organisational characteristics were found to have a moderating effect ($p > 0.05$).

Validity and reliability of analysis
The R^2 values (25.7 and 35.9 per cent) recorded in the regression models were highly acceptable from a review of the R^2 values of other construction-management studies, using

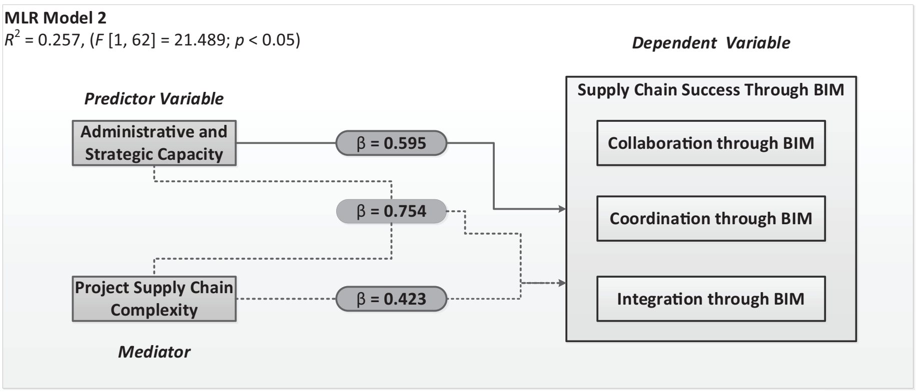

Figure 2. Summary of regression analysis for supply chain success through BIM modelling

similar methods (4-26 per cent) (Omoregie, 2006; Ankrah, 2007). According to Harris (1985), reliance on the ratio of number of predictor variables ("*p*") to observations ("*N*") is the most appropriate method for establishing sample size adequacy in regression modelling. From a review of empirical studies, Howell (1997) suggests that "*N*" is adequate when it exceeds "*p*" by between 40 and 50. Following Harris (1985) and Howells (1997), the ratio of observations to predictors in this study satisfies the requirements for conduct of regression analysis. Furthermore, Cronbach's Alpha values (0.810-0.93) were indicative of highly reliable scales (Field, 2013) for both success and BIM capability variables, respectively.

Discussion of findings

A review of the relationship between the significant predictors of BIM modelling success and constituent success indicators revealed that *staff experience* has a higher degree of association with BIM modelling quality and delivery within budget, while suitability of *proposed methodology* is more associated with BIM delivery within schedule. With regard to CSC success through BIM, *administrative and strategic capacity* emerged as the only capability attribute with a meaningful contribution, albeit dependent on the level of CSC complexity (i.e. large, multi-layered CSC characterised by substantial lower-tier BIM involvement or use). The results suggest that BIM is likely to influence collaboration, integration and coordination on projects with more complex supply chains. *Administrative and strategic capacity* was also found to influence the attainment of integration, more when compared to coordination and collaboration of the CSC.

According to Du *et al.* (2014), the key performance expectations of BIM include information quality, as well as timely and cost-effective delivery. This includes the accuracy of data in models and, generally, the extent to which modelling conforms to requirements. From the findings, individual skills at developing BIM models and appropriate execution planning are found to constitute the most critical capability attributes that influence successful delivery of BIM.

In circumstances where the traditional view of success (quality, schedule and budget) is a concern, individual competencies should be the most important consideration. According to Succar *et al.* (2013), such individual BIM skills should be both procedural and applied or conceptual knowledge. While there are multiple areas of performance, Succar *et al.* (2013) have not advocated the specific areas within which experience is most likely to influence success. This study, however, reveals that individual experience influences tangible performance expectations of BIM, specifically, in relation to the quality of modelling, delivery within budget and on schedule. Smits *et al.* (2016), on the other hand, found strategic capability as the most influential on project cost, time and quality performance. This contrast may, however, be explained by the fact that Smits *et al.* (2016) investigated the influence of BIM maturity on project-level success factors rather than the success in the delivery of BIM itself on the project.

While planning has always been recommended for the attainment of project objectives, no empirical studies have explicitly investigated the impact of BEPs on successful delivery on projects. However, the ability to develop an effective plan or method in response to a project brief or need is identified as key to BIM modelling success, more specifically, delivery within schedule. Standards documents such as the CIC protocol (CIC, 2013b) and PAS1192:2 (2013) have promoted the concept of BEPs. Other studies have highlighted the importance of BEP to project success (Al-Ahbabi and Alshawi, 2015). However, no study has sought to establish the relationship between proposed methodology (project-specific BEPs) and delivery success in practice, especially through an empirical assessment. From the findings, suitable *proposed methodology* (e.g. a BEP) is mostly associated with delivery within schedule. This study aligns with a wider view within construction that effective planning and allocation of CSC resources affect timely deliveries of BIM output (Murphy, 2014). The delivery of quality BIM models within budget is mostly associated with higher levels of staff experience. This also aligns with the views that construction organisations are able to better conform to requirements when the workforce possesses adequate levels of procedural skill and knowledge (Arditi and Gunaydin, 1999). The finding further supports the notion that years of repetitive usage of BIM or related technologies aid individuals to develop core or domain competencies that assure value. This value is mostly evident in the quality of the deliverables and the ability to deliver BIM within cost, but not as much for timely delivery. Furthermore, staff expertise and proposed methodology have featured among the most important predictors of success in construction studies in general (Doloi, 2009).

Administrative and strategic capacity emerged as the single most important influencer of CSC success through BIM. This variable provides evidence of effective vision, planning, development and management of resources in BIM implementation within an organisation. While other studies have highlighted strategic factors as important to BIM capability overall (Murphy, 2014; Giel and Issa, 2016), this study indicates, it primarily influences the attainment of collaboration, coordination and integration in the CSC context. The attainment of CSC success through BIM was, however, mediated by the level of complexity of the project CSC. Consequently, more complex supply chains present more opportunities for achieving collaboration, coordination and integration through strategic implementation of BIM (Vrijhoef, 2011; Manu, 2014; Papadonikolaki *et al.*, 2015a).

According to Giel and Issa (2014), strategic capacity refers to factors that impact an organisation's ability to plan and develop courses of action for BIM execution. Administrative capacity also refers to how organisations manage resources to meet desired goals associated with their internal BIM execution strategies (Giel and Issa, 2016). Similarly, the following factors constitute administrative and strategic capacity: *IT vision and mission*, *quality of BIM implementation strategy* and *BIM R&D*. It is still not clear to what extent the construction industry is leveraging BIM to achieve CSC objectives; however, this study highlights the importance of strategic and administrative issues for attaining these objectives. The findings suggest that strategic objectives of the CSC must be incorporated in the long-term planning activities as well as allocation of resources in BIM implementation to attain success. According to Papadonikolaki *et al.* (2015a), CSC BIM performance is underpinned by strategy that is normally linked to effective long-term and commercially driven factors. Thus, while there are operational benefits of BIM use, its success in the CSC is largely dependent on the overarching strategy, as well as management of BIM implementation resources. Consonant with these assertions, Manu (2014) recommended the incorporation of BIM capability criteria in performance management of the CSC. According to Manu (2014), this improves the strategic management of the CSC, which currently focusses mostly on factors such as health and safety performance, financial health and programme compliance.

Evidence of BIM R&D within an organisation is a likely indicator of ability to leverage BIM for the attainment of CSC objectives (Succar, 2010). The findings, therefore, support a notion that the success of BIM application for CSC operations is not dependent on procedural, process or technology-related capacity but rather management and strategy-level factors. Thus, it can be inferred that BIM enhances strategic functions of the supply chain much more than operational areas, which arguably are still at the infancy of BIM application (Papadonikolaki *et al.*, 2015a). This finding is consistent with the findings of Smits *et al.* (2016) that strategic BIM process maturity influences project-level performance rather than the performance in the attainment of BIM deliverables themselves.

Respondents recounted that the attainment of CSC success through BIM was generally not as high as the levels of BIM modelling success (quality, schedule and budget). This confirms existing evidence that CSC and CSC-management objectives are not solely met by the use of technologies such as BIM but also other commercial and structural imperatives (Cerovsek, 2011; Antwi-Afaria *et al.*, 2018).

Conclusions

The findings provide empirical evidence on the need for the prioritisation of BIM capability attributes based on their relative influence on desirable success indicators. Thus, the prioritisation of criteria during capability assessments must be based on their relative contribution to all relevant areas of success to provide a holistic view. Prioritisation of criteria in existing frameworks are, however, based only on the relative importance of such criteria as capability metrics, rather than their relative contribution to various areas of success, as investigated in this study. Furthermore, capability or maturity only denotes the basic abilities to perform BIM-related tasks efficiently, rather than the actual attainment of the objectives expected from BIM deployment.

This study has provided insights about the influence of key capability attributes on other BIM deployment objectives, such as the quality of BIM; delivery of BIM on schedule; delivery of BIM within budget; and collaboration, coordination and the integration of CSC through BIM. While some studies have sought to explore the influence of BIM maturity elements on project success in general, no studies have investigated the influence of CSC BIM capability on the successful delivery of BIM itself. This is, however, a more meaningful measurement, given overall project success is presumably influenced by many other factors.

Study implications for practice

The main implications of the research findings for practice are two-fold: development of BIM capability and maturity; and development of procurement policies. These are elaborated as follows.

Building information modelling capability and maturity development

- The BIM capability attributes and their priority rankings would enable organisations to self-examine their internal capacity and maturity for the purposes of performance management and improvement. This would aid the identification of areas of strength, weaknesses and opportunities for consolidating BIM capability within construction industry organisations overall. Furthermore, these organisations can identify BIM implementation areas that require prioritisation, such that there is efficient allocation of investment in BIM capacity building. On this note, this research has demonstrated the need for prioritising administrative and strategic capacity for supply chain BIM use success and, on the other hand, staff experience and project execution planning (i.e. methodology) for more efficient BIM delivery performance.

Procurement policy development

- In spite of government mandate for adoption of BIM, particularly, in the UK and more recently across Europe, Asia and the Middle East, there remains no policy directives regarding capacity building. The research findings, however, have implications for BIM implementation on projects, particularly in relation to procurement. Clients, main contractors and principal suppliers can prioritise selection criteria, such that they are consistent with the research findings. This is important, given relevant documentations for procurement such as British Standards Institution PAS 91:2013 (2013) and the

Pennsylvania State Planning Guide (CICa, 2013), which do not prescribe selection criteria priority weightings for selection of organisations on BIM projects.

- From the findings, the key determinants of success from supply chain integration perspective have been established to be strategic and administrative BIM process maturity. This distinction is critical to current efforts for the adoption of integrated procurement methods such as integrated project delivery (Porwal and Hewage, 2013), which promises to integrate supply chains more effectively through BIM.

This study provides an empirically supported justification for propositions about the role of BIM capability in BIM delivery success, as espoused within literature. It further shows the multidimensional nature of this relationship, which hitherto has been viewed as a unilateral and technologically deterministic concept. It brings into focus the need for prioritising BIM capability criteria based on their contribution to delivery success. The findings debunk the hard technology-centric nature of BIM capability discourse. Criteria relied on for assessing BIM capability in most existing frameworks are often hard technology-centric. Thus, most capability frameworks align with a hard technological deterministic view of BIM, where the technology artefacts and resources are primary determinants of BIM capability and delivery success. While this study acknowledges the importance of technological capacities, such as hardware and software, it places more emphasis on the role of specific information process maturity and collective knowledge, skills and attitudes within a CSC organisation.

Limitations and implications for future research

Future studies could adopt more longitudinal approaches to explore the evolution of BIM maturity and how that influences delivery success over longer periods, as opposed to the cross-sectional focus of this study. A review of the survey respondents' backgrounds revealed that many of the CSC organisations assessed were design consultants, as well as main and sub-contractor organisations, with high-level design responsibility and from middle to top tiers of the CSC. This is largely owing to reported lack of usage of BIM by lower-tier CSC organisations that often have less design responsibility and digital technology expertise. Future studies could, however, focus on the lower tiers of the CSC, especially when BIM adoption increases in this segment of the market. Lastly, some key BIM delivery success factors have been examined, albeit in a supply chain and project model delivery perspective. Future studies could consider other dimensions of success, especially at project level, with consideration of other non-BIM capability indicators.

References

Abdirad, H. (2017), "Metric-based BIM implementation assessment: a review of research and practice", *Architectural Engineering and Design Management*, Vol. 13 No. 1, pp. 52-78.

Adriaanse, A. (2007), "The use of interorganisational ICT in construction projects: a critical perspective", PhD thesis, University of Twente.

Al-Ahbabi, M. and Alshawi, M. (2015), "BIM for client organisations: a continuous improvement approach", *Construction Innovation*, Vol. 15 No. 4, pp. 402-408.

Al-Zahrani, J.I. and Emsley, M.W. (2013), "The impact of contractors' attributes on construction project success: a post construction evaluation", *International Journal of Project Management*, Vol. 31 No. 2, pp. 313-322.

Ankrah, N.A. (2007), "An investigation into the impact of culture on construction project performance", PhD thesis, School of Engineering and the Built Environment, University of Wolverhampton.

Antwi-Afaria, M.F., Lib, F., Pärnc, E.A. and Edwards, D.J. (2018), "Critical success factors for implementing building information modelling (BIM): a longitudinal review", *Automation in Construction*, Vol. 91, pp. 100-110.

Anvuur, A.M. (2008), "Cooperation in construction projects: concept, antecedents and strategies", Unpublished thesis, The University of Hong Kong, Hong Kong.

Arayici, Y., Coates, P., Koskela, L., Kagioglou, M., Usher, C. and O'Reilly, K. (2011), "Technology adoption in the BIM implementation for lean architectural practice", *Automation in Construction*, Vol. 20 No. 2, pp. 89-195.

Arditi, D. and Gunaydin, H. (1999), "Perceptions of process quality in building projects", *Journal of Management in Engineering*, Vol. 15 No. 2, pp. 43-53.

Arslan, G., Kivrak, S., Birgonul, M.T. and Dikmen, I. (2008), "Improving sub-contractor selection process in construction projects: web-based sub-contractor evaluation system (WEBSES)", *Automation in Construction*, Vol. 17 No. 4, pp. 480-488.

Atkin, B. (1995), "Information management of construction projects", in Brandon, P. and Betts, M. (Eds), *Integrated Construction Information*, E and FN Spon, London. pp. 291-315.

Azzouz, A. and Hill, P. (2017), "Hunting for perfection: how arup measures BIM maturity on projects worldwide", *Construction Research and Innovation*, Vol. 8 No. 2, pp. 49-54.

Best, R. and Smith, N. (2005), "Statistics and the peer review process in construction research", in Sidwell, A.C. (Ed.), *The Queensland University of Technology Research Week International Conference*, 4-8 July, *Brisbane*, pp. 1027-1033.

BIS (2011), "Government construction strategy", Department of Business and Innovation, London.

BIS (2013a), "Industrial strategy: Government and industry in partnership: construction 2025", Report number: URN BIS/13/955, Department for Business, Innovation and Skills, London.

BIS (2013b), "Supply chain analysis into the construction industry: a report for the construction industrial strategy", Report number: BIS Research Paper No. 145, Department for Business, Innovation and Skills, London.

Brace, N., Kemp, R. and Snelgar, R. (2003), *SPSS for Psychologists: A Guide to Data Analysis Using SPSS for Windows*, Palgrave Macmillan, Basingstoke.

Cerovsek, T. (2011), "A review and outlook for a 'building information model' (BIM): a multi-standpoint framework for technological development", *Advance Engineering Informatics*, Vol. 25 No. 2, pp. 224-244.

CIC (2013a), *BIM Planning Guide for Facility Owners: Computer Integrated Construction (CIC)*, PA State University, PA.

CIC (2013b), "Building information model (BIM) protocol: standard protocol for use in projects using building information models", Construction Industry Council, London.

Creative Research Systems (2003), "The survey system", available at: www.surveysystem.com/index.htm (accessed 12 January 2015).

Creswell, J.W. (2007), *Qualitative Inquiry and Research Design: Choosing among Five Approaches*, Sage, Thousand Oaks.

Dainty, A.R.J., Briscoe, G.H. and Millett, S.J. (2001), "New perspectives on construction supply chain integration", *Supply Chain Management: An International Journal*, Vol. 6Vol. No. 4, pp. 163-173.

Dalkey, N. and Helmer, O. (1963), "An experimental application of the delphi method to the use of experts", *Management Science*, Vol. 9 No. 3, pp. 458-467.

Denscombe, M. (2010), *The Good Research Guide for Small Scale Social Research Projects*, 4th ed., Open University Press, London.

Dib, H., Chen, Y. and Cox, R.F. (2012), "A framework for measuring building information modeling maturity based on perception of practitioners and academics outside the USA", *Proceedings 29th International Conference CIB W78 2012, CIB, Beirut, Lebanon*, 17-19 October.

Doloi, H. (2009), "Analysis of pre-qualification criteria in contractor selection and their impacts on project success", *Construction Management and Economics*, Vol. 27 No. 12, pp. 1245-1263.

Du, J., Liu, R. and Issa, R. (2014), "BIM cloud score: benchmarking BIM performance", *Journal of Construction Engineering and Management*, Vol. 140 No. 11.

Field, A. (2013), *Discovering Statistics Using SPSS*, 4th ed., Sage Publications, London.

Giel, B. and Issa, R. (2014), "Framework for evaluating the BIM competencies of building owners", *Computers in Civil and Building Engineering*, American Society of Civil Engineers (ASCE), Reston, VA, pp. 552-559.

Giel, B. and Issa, R. (2016), "Framework for evaluating the BIM competencies of facility owners", *Journal of Management in Engineering*, Vol. 32 No. 1, pp. 1-15.

Guest, G., Arwen, B. and Laura, J. (2006), "How many interviews are enough? An experiment with data saturation and variability", *Field Methods*, Vol. 18 No. 1, pp. 59-82.

Hair, J.F., Black, W.C., Babin, B.J., Anderson, R.E. and Tatham, R.L. (2010), *Multivariate Data Analysis with Readings*, 7th ed., Prentice Hall, NJ.

Harris, R.J. (1985), *A Primer of Multivariate Statistics*, 2nd ed., Academic Press, New York, NY.

Hallowell, M. and Gambatese, J. (2010), "Qualitative research: application of the delphi method to CEM research", *Journal of Construction Engineering and Management*, Vol. 136 No. 1, pp. 99-107.

Hatush, Z. and Skitmore, M. (1997), "Evaluating contractor prequalification data: selection criteria and project success factors", *Construction Management and Economics*, Vol. 15 No. 2, pp. 129-147.

Hayes, A.F. (2009), "Beyond Baron and Kenny: statistical mediation analysis in the new millennium", *Communication Monographs*, Vol. 76 No. 4, pp. 408-420.

Hayes, A.F. (2016), "My macros and code for SPSS and SAS", available at: www.processmacro.org/index.html (accessed 3 January 2016).

Holt, G.D. (1998), "Which contractor selection methodology?", *International Journal of Project Management*, Vol. 16 No. 3, pp. 153-164.

Howell, D.C. (1997), *Statistical Methods for Psychology*, 4th ed., Wadsworth, Belmont, CA.

Kam, C., ; Rinella, T. and Oldfield, J. (2013a), "Using objectified measures to realize the promise of BIM", *Journal of National Institute of Building Science (JNIBS)*, Vol. 1 No. 1, pp. 14-18.

Kam, C. Rinella, T. Mak, D. and Oldfield, J. (2012), "BIMSCORE: GPS for BIM navigation: from aspirations to quantitative measures of success", Practical BIM 2012: Management, Implementation Coordination and Evaluation, Los Angeles, CA.

Kam, C., Senaratna, D., Xiao, Y. and McKinney, B. (2013b), "The VDC scorecard: evaluation of AEC projects and industry trends", CIFE Working Paper WP136, Stanford University: Center for Integrated Facility Engineering (CIFE).

Kam, C., Senaratna, D., McKinney, B., Xiao, Y. and Song, M. (2014), "The VDC scorecard: formulation and validation", CIFE Working Paper WP135, Stanford university: Center for integrated facility engineering (CIFE).

Khalfan, M., Khan, H. and Maqsood, T. (2015), "Building information model and supply chain integration: a review", *Journal of Economics Business and Management*, Vol. 3 No. 9, pp. 912-916.

Keavney, M., Mitchell, C. and Munn, D. (2013), "An examination of the potential of building information modelling to increase the efficiency of Irish contractors on design and build projects", *Proceedings International Virtual Conference*, 25-29 March, *University of Zilina*.

Kenny, D.A. (1986), "The moderator-mediator variable distinction in social psychological research: conceptual, strategic, and statistical considerations", *Journal of Personality and Social Psychology*, Vol. 51, pp. 1173-1182.

Lonngren, H.M., Rosenkranz, C. and Kolbe, H. (2010), "Aggregated construction supply chains: success factors in implementation of strategic partnerships", *Supply Chain Management: An International Journal*, Vol. 15 No. 5, pp. 404 -411.

Mahamadu, A.M., Mahdjoubi, L. and Booth, C. (2017), "Critical BIM qualification criteria for construction pre-qualification and selection", *Architectural Engineering and Design Management*, Vol. 13 No. 5, doi: 10.1080/17452007.2017.1296812.

Manu, P.A. (2012), "An investigation into the accident causal influence of construction project features", PhD Thesis, School of Technology, University of Wolverhampton.

Manu, E. (2014), "Supply chain management practices in construction and inter-organizational trust dynamics", PhD Thesis, School of Technology, University of Wolverhampton.

Mom, M., Tsai, M. and Hsieh, S. (2011), "On decision making and technology-implementing factors for BIM adoption", in Bargstaedt, H.J. and Ailland, K. (Eds), *Proceedings of the 11th International Conference on Construction Applications of Virtual Reality*, 3-4 November, *Bauhaus-Universität Weimar*, *Weimar*, pp. 217-229.

Mom, M., Tsai, M. and Hsieh, S. (2014), "Developing critical success factors for the assessment of BIM technology adoption: Part II: analysis and results", *Journal of the Chinese Institute of Engineering*, Vol. 37 No. 7, pp. 859-868.

Murphy, M.E. (2014), "Implementing innovation: a stakeholder competency-based approach for BIM", *Construction Innovation*, Vol. 14 No. 4, pp. 433-452.

Navendren, D., Manu, P., Shelbourn, M. and Mahamadu, A. (2014), "Challenges to building information modelling implementation in the UK: designers' perspectives", in Raiden, A.B. and Aboagye-Nimo, E. (Eds), *Proceedings the 30th Annual Association of Researchers in Construction Management (ARCOM) Conference*, *Portsmouth*, pp. 733-742.

NBS (2016), "National BIM Report 2016", National Building Specification, London.

NIBS (2012), "National building information modeling standard – version 2.0-chapter 5.2 Minimum BIM", National Institute of Building.

Omoregie, A. (2006), "Blueprints for infrastructure and service delivery in Sub-Saharan Africa", PhD Thesis, The Leicester School of Architecture, De Montfort University, Leicester.

Papadonikolaki, E., Vrijhoef, R. and Wamelink, H. (2015a), "BIM adoption in integrated supply chains: a multiple case study", in Raidén, A.B. and Aboagye-Nimo, E. (Eds), *Proceedings of the 31st Annual Association of Researchers in Construction Management (ARCOM) Conference*, 7-9 September, *Lincoln*, pp. 631-640.

Papadonikolaki, E., Vrijhoef, R. and Wamelink, H. (2015b), "Supply chain integration with BIM: a graph-based model", *Structural Survey*, Vol. 33 No. 3, pp. 257-277.

Papadonikolaki, E., Vrijhoef, R. and Wamelink, H. (2016), "The interdependences of BIM and supply chain partnering: empirical explorations", *Architectural. Engineering and Design Management*, Vol. 12 No. 6, pp. 476-494.

PAS 91:2013 (2013), "Construction prequalification questionnaires", British Standards Institution (BSI).

PAS1192:2 (2013), "Specification for information management for the capital delivery phase of construction projects using building information modelling", Report number: Part 2, British Standards Institution (BSI).

Porwal, A. and Hewage, K.N. (2013), "Building information modeling (BIM) partnering framework for public construction projects", *Automation in Construction*, Vol. 31, pp. 204-214.

Pryke, S. (2009), *Construction Supply Chain Management*, 1st ed., Blackwell Publishing, Chichester.

Saleh, Y. and Alshawi, M. (2005), "An alternative model for measuring the success of IS projects: the GPIS model", *Journal of Enterprise Information Management*, Vol. 18 No. 1, pp. 47-63.

Salmeron, J.L. (2010), "Fuzzy cognitive maps-based IT projects risks scenarios", in Glykas, M. (Ed), *Fuzzy Cognitive Maps: Advances in Theory, Methodology, Tools and Applications. Studies in Fuzziness and Soft Computing*, Verlag Berlin Heidelberg, Springer, Vol. 247, pp. 201-216.

Sebastian, R. and van Berlo, L. (2010), "Tool for benchmarking BIM performance of design, engineering and construction firms in The Netherlands", *Architectural Engineering and Design Management*, Vol. 6 No. 4, pp. 254-263.

Smits, W. van Buiten, M. and Hartmann, T. (2016), "Yield-to-BIM: impacts of BIM maturity on project performance", Building Research and Information, doi: 10.1080/09613218.2016.1190579.

Succar, B. (2009), "Building information modelling framework: a research and delivery foundation for industry stakeholders", *Automation in Construction*, Vol. 18 No. 3, pp. 57-375.

Succar, B. (2010), "Building information modelling maturity matrix", *Handbook of Research on Building Information Modeling and Construction Informatics: Concepts and Technologies*, IGI, Hershey, Pennsylvania, pp. 65-103.

Succar, B., Sher, W. and Williams, A. (2012), "Measuring BIM performance: five metrics", *Architectural Engineering and Design Management*, Vol. 8 No. 2, pp. 120-142.

Succar, B., Sher, W. and Williams, A. (2013), "An integrated approach to BIM competency assessment, acquisition and application", *Automation in Construction*, Vol. 35, pp. 174-189.

Takim, R. and Akintoye, A. (2002), "Performance indicators for successful construction project performance", in Greenwood, D. (Ed.), *Proceedings 18th Annual Association of Researchers in Construction Management (ARCOM) Conference*, 2-4 September, Vol. 2, *Northumbria*, pp. 545-555.

Thomas, J. and Harden, A. (2008), "Methods for the thematic synthesis of qualitative research in systematic reviews", *BMC Medical Research Methodology*, Vol. 8 No. 1, pp. 45-45.

Tsai, M., Mom, M. and Hsieh, S. (2014), "Developing critical success factors for the assessment of BIM technology adoption: part I: methodology and survey", *Journal of the Chinese Institute of Engineering*, Vol. 37 No. 7, pp. 845-858.

Van Berlo, L., Dikkmans, T., Hendriks, H., Spekkink, D. and Pel, W. (2012), "Benchmark of BIM performance in The Netherlands", *Proceedings 29th International Conference CIB W78 2012, Beirut, Lebanon*, 17-19 October.

Vrijhoef, R. (2011), "Supply chain integration in the building industry: the emergence of integrated and repetitive strategies in a fragmented and Project-Driven industry", IOS Press, Amsterdam.

Yin, K.R. (2003), *Case Study Research: Design and Methods*, Sage Publications, Thousand Oaks, CA.

Further reading

Bliese, P.D. (2000), "Within group agreement, non-independence and reliability", in Klein, K.J. and Kozlowski, S.W.J. (Eds), *Multilevel Theory, Research, and Methods in Organizations: Foundations, Extensions, and New Directions*, Jossey-Bass, San Francisco.

Creswell, J.W. (2003), *Research Design: Qualitative, Quantitative, and Mixed Method Approaches*, 2nd ed., Sage, CA.

Holt, G.D., Olomolaiye, P.O. and Harris, F.C. (1994), "Evaluating prequalification criteria in contractor selection", *Building and Environment*, Vol. 29 No. 4, pp. 437-448.

Corresponding author
Abdul-Majeed Mahamadu can be contacted at: Abdul.Mahamadu@uwe.ac.uk