The Importance of BIM Capability Assessment: An Evaluation of Post-Selection Performance of Organisations on Construction Projects

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ABSTRACT

Purpose: The emergence of Building Information Modelling (BIM) has led to the need for pre-qualification and selection of organisations capable of working within a BIM environment. Several criteria have been proposed for the assessment of an organisations BIM capability during the pre-qualification and selection phase of projects. However, no studies have sought to empirically establish whether organisations selected on the basis of such criteria have actually been the most successful at delivering BIM on projects. The aim of the study is to address the aforementioned gap through a comparison of predicted BIM capability and post-selection performance.

Design/methodology/approach: BIM capability of firms in a case study was predicted using 28 BIM pre-qualification and selection criteria, prioritised based on their perceived contribution to BIM delivery success from a survey of practitioners on BIM-enabled projects. The comparison of predicted BIM capability and post-selection performance was on the other hand achieved through the application of the Technique to Order Preference by Similarity to Ideal Solution and Fuzzy Sets Theory (Fuzzy-TOPSIS).

Findings: Findings underscore the reliability of the 28 BIM pre-qualification and selection criteria as well as the priority weightings proposed for their use in predicting BIM capability and likelihood of performance. The findings have highlighted the importance of criteria related as previous BIM use experience as well as information processing maturity as critical indicators of the capability of organisations particularly design firms.

Originality/value: Overall, the findings highlight the need for prioritisation of BIM pre-qualification and selection criteria on the basis of their actual contribution to delivery success from post-selection evaluation of performance.

Keyword: BIM, Capability, Case Study, Competence, Performance

INTRODUCTION

Communication bottlenecks and lack of collaboration continue to impede performance of the construction industry resulting in the recent promotion of Building Information Modelling (BIM) as a technologically driven process improvement platform (Gu and London, 2010). BIM has been described as the epitome of policies, processes and technologies that will enable the construction industry to generate, manage and store project data in digital formats for lifecycle management (Eastman et al., 2008). BIM is expected to bridge communications' gaps as well as poor lifecycle data utilisation issues that are core to the current process inefficiencies associated with the industry (Succar, 2009). However, despite organisations efforts to develop BIM capability, there remains a lack of standardised approach for evaluating competence and capability to deliver BIM on projects. Recently, there has been a proliferation of frameworks for BIM capability assessment with the proposition of several capability indicating criteria and attributes. Few studies have sought to ascertain whether these criteria are actually indicative of the ability to successfully deliver BIM on a project (Van Berlo et al., 2012). This is even more important during pre-qualification and selection process where such criteria are required to predict the organisations most likely to perform even before they are contracted to join a project team. The aim of this study is to conduct a comparative analysis of predicted BIM capability and post-selection performance using a case study of design firms selected by a main contractor to deliver BIM on their projects within the UK.

To facilitate understanding, the remainder of this article has been divided into 5 main sections. Firstly, an overview of the BIM capability assessment for pre-qualification and selection is presented. This is followed by a detailed discussion on the chosen research method for this study. Thirdly, following from the research methods, the results and findings are discussed. This is followed by a discussion on the research findings. The last section presents concluding remarks.

BIM CAPABILITY ASSESSMENT FOR PRE-QUALIFICATION AND SELECTION

In order to examine existing studies about BIM capability assessment, it is imperative to provide a working definition of BIM. Based on the literature, BIM has been defined differently by different authors. Some of the definitions are misleading and at times so skewed and limited in scope (Succar, 2009). For example, BIM has been referred to as a type of software, others have referred to BIM as a 3D virtual model of a building (NBS, 2013). Other descriptions of BIM, a process for design, construction and management of buildings (Succar, 2009; NBS, 2013). Instead of engaging with the aforementioned subtleties in the various definitions or misconceptions, albeit limited in scope, more encompassing definitions will be examined. Mott MacDonald defines BIM as a “coordinated set of processes, supported by technology, that add value by creating, managing and sharing the properties of an asset throughout its lifecycle (MM, 2017). These models incorporate graphic, physical, commercial, environmental and operational data. The UK Construction Industry Council describes BIM as an innovative and collaborative way of working and also a process that is underpinned by digital workflows for more efficient design, construction and maintenance of the built environment (CIC, 2013a). What emerges from these definitions is the fact that BIM can include the process, technology, people, policy and legal dimensions (Succar, 2009). The process dimension entails the activities related to the sharing or exchange of information, while the technology include the different software and hardware required to support the processes. The people dimension is about the professionals involved in the delivery of a BIM compliant project (e.g. BIM coordinator) and attitudes of people vis-à-vis BIM adoption. The policy dimension is about statutory regulations required to promote the uptake of BIM, while the legal dimension of BIM is about the laws that regulates the implications of sharing building model information or working in a collaborative environment. Based on this definition, this work will cut across the process, technology and the people dimensions. These is because these dimensions are about the delivery of projects, what capacity of contractors and subcontractors are directly required.

An emerging core competence area of pre-qualification and selection is BIM maturity of organisations (Mahamadu *et al.,* 2017). As a result, several BIM standards and national implementation agenda require the assessment of BIM capability of project teams prior to selection. For example in the UK, BIM execution plans must include a Supply Chain Capability Summary (SCCS) which indicates the BIM competence of all firms on the supply chain of principal suppliers and contractors (PAS1192:2, 2013). Similar frameworks for assessing organisational BIM capability prior to project selection or commencement have been proposed in Scotland (Fenby-Taylor et al., 2016), the USA (CIC, 2013b), the Netherlands (van Berlo *et al.,* 2012) and also by major consulting and construction firms such as Skanska (CPIx 2013) and ARUP (Azzouz and Hill, 2017) across the globe.

These emerging standards, frameworks and tools have provided the basis for the identification of appropriate BIM pre-qualification and selection criteria (Succar, 2009; van Berlo *et al.,* 2012; CIC, 2013b; Kam *et al.,* 2013; Giel and Issa, 2014; Mahamadu et al., 2017). The UK government standard pre-qualification questionnaires now include a section specifically dedicated for BIM capability (PAS 91, 2013) albeit only generically requires assessment of BIM competence and experience without detailed delineation of the sub-attributes that indicate competence and experience. The PAS1192:2, 2013 and now BS EN ISO 19650 require demonstration of BIM capability in terms of IT resources, roles and responsibilities as well as experience from catalogue of past projects. This was referred to in the PAS1192:2 as the Supply Chain BIM Capability Summary (SCCS), although specific methodology for assessing this is not prescribed in these standards. Succar *et al.,* (2012) proposed a BIM capability framework of criteria namely technology, process and policy. The technology dimension of this framework refers to physical artefacts including software, hardware and network capability while process dimension encompasses attributes such as BIM resources, activities and workflows. The policy dimension of Succar's (2012) framework covers procedures related contracts, benchmarks and guidance documents that support BIM implementation. Dib *et al.* (2012) classified capability criteria as planning and management, process, team structure, hardware, process definition and information management. The Pennsylvania State University BIM guide (CIC, 2013b) classifies capability factors similarly as strategy, BIM uses, process, information, infrastructure and personnel. Mahamadu et al., (2017) on the other hand, classified BIM capability attributes for pre-qualification and selection activities namely, competence, capacity and resources, culture and attitude and cost.

Despite these propositions for BIM capability assessment, there is less research to establish whether organisations selected on the basis of such criteria actually deliver to expectations after they are selected. A few studies have explored the relationship between BIM maturity and project performance generally (Smits *et al.,* 2016). Other studies have specifically explored the influence of BIM qualification criteria on BIM delivery success to aid pre-selection prediction of capability (Mahamadu *et al.,* 2017). Most of these BIM capability and maturity studies have however only proposed assessment criteria as precursors of success though the actual performance of firms post selection has not yet been explored (Succar, 2009; van Berlo *et al.,* 2012; CIC, 2013b; Kam *et al.,* 2013; Giel and Issa, 2014). These studies have also led to varied views about criteria importance and therefore the weightings to be applied to them when used as BIM capability assessment metrics. For instance, Smits *et al.,* (2016) survey of Dutch firms established that there are statistically reliable associations between BIM maturity and project success indicators (time and cost) though findings were inconclusive on the influence of BIM maturity on project quality. Mahamadu *et al.,* (2017) found that while technological infrastructure capability is perceived as very important qualification criteria, their actual contribution to delivery success is low. According to the CIC (2013b) framework, strategy and personnel competencies are weighted as the most important criteria in capability assessment. Giel and Issa (2014) prioritised BIM operational competencies of owner organisations as most important followed by strategic competencies. van Berlo *et al.,* (2012) on the other hand rated mentality and BIM culture related attributes as most important followed by information processing competencies. Whereas these frameworks are proposed for different contexts of evaluation, they highlight significant variations in the perceived importance of BIM capability assessment criteria. More so, they underscore the need to ascertain criteria importance based on their actual contribution to delivery performance in practice. Despite propositions from previous studies (Mahamadu et al 2017; CIC, 2013b; Kam *et al.,* 2013; Giel and Issa, 2014), there remains no validation of the proposed attributes through a post-selection evaluation of firms' a performance. This highlights the need for post-selection performance evaluations to ascertain whether organisations selected on the basis of BIM capability criteria actually perform on projects as a validation of priority weightings given to such criteria in current frameworks.

Review of Methodologies for Evaluating Capability and Performance

Over the past few decades, there has been greater recognition of the need for the adoption of improved evaluation techniques assessing capability of firms for the purposes of procurement or selection. This has led to the proposition of various computational approaches. One of the basic approaches that has been proposed is the dimensional weighting model for the aggregation of weighted ratings from questionnaires (Jaselskis & Russell, 1991). Holt et al. (1994) developed a model based on multi-attribute analysis and utility theory. Likewise, Ng (2001) proposed a case-based reasoning system for the capture and reuse of experimental knowledge experts to facilitate evaluation. El-Abassy et al. (2013) put forward a model based on the integration of Analytical Network Process (ANP) and Monte Carlo simulation for prioritising highway contractor's capability. However, Nguyen (1985) addressed a critical limitation of these models by incorporating Fuzzy Set Theory in the developing of a contractor capability evaluation model. This paved the way for the development of a new generation of frameworks, including Nieto-Morote & Rus-Vila, (2012) and Plebankiewicz (2012), who have similarly developed models based on Fuzzy Set Theory. Hosny et al. (2013) proposed a contractor evaluation model based fuzzy-Analytical Hierarchy Process (AHP). The fuzzy set approach allows mathematical modelling of uncertainty and vagueness of subjective judgements associated with evaluation made by human decision makers. Despite these advances, many limitations still prevail, depending on the methodologies. Some of the proposed methodologies are sometimes restrictive due to their complexity and a need for specialist mathematical knowledge in order to use them (Nieto-Morote & Rus-Vila, 2012). Others are rather simplistic failing to model the uncertainty and vagueness associated with evaluation of alternative firms in multi-attribute scenarios (Plebankiewicz, 2012). Thus, there remains the need for integrated models that complement each other in order to eliminate the weaknesses of either. More importantly, the existing models have not been developed with an ability to predict BIM capability. Although, multi-criteria selection methods such as TOPSIS (Alireza Ahmadian, et al., 2017) and the Voting-AHP (Gbadamosi et al., 2019) are increasingly being incorporated within BIM as decision support mechanisms, not many studies have incorporated them into the BIM performance evaluation of organisations. Furthermore, there is the need for their adoption in an integrated way such that they complement each other's weaknesses. For instance integrating fuzzy logic within a TOPSIS framework allows modelling of vagueness and subjectivity in decision scenarios with a robust computational method for evaluation (Dağdevirena et al., 2009).

In order to address the aforementioned gaps this study adopted Fuzzy-TOPSIS as comparison framework for predicted BIM capability versus post-selection performance on a case study of design firms on a main contractor's supply chain (for the delivery of BIM projects).

RESEARCH METHODOLOGY

This study sought to ascertain the reliability of BIM qualification criteria as well as their proposed weightings through a comparison of predicted BIM capability and post-selection performance of a case study of design firms (*n* = 5) on BIM projects in a main contractor supply chain. The predicted BIM capability was assessed with the aid of 28 BIM pre-qualification and selection criteria proposed by Mahamadu *et al.,* (2017). Mahamadu *et al.,* (2017) criteria is based on a consolidation of criteria from previous frameworks, assessment standards, interviews and Delphi studies thus deemed as suitable summary and classification of BIM capability criteria for pre-qualification and selection purposes. In phase 1, the 28 pre-qualification and selection criteria were prioritised based on their perceived contribution to BIM delivery success from a survey of practitioners on BIM-enabled projects (*n* = 64). The prioritisation was based on computation of mean weighted contributions as proposed by Giel and Issa (2014) in the determination of weights for BIM client competence.

The comparison of predicted BIM capability and post-selection performance was assessed in phase 2 with the aid of the Technique to Order Preference by Similarity to Ideal Solution and Fuzzy Set Theory (Fuzzy-TOPSIS). The BIM capability of five top tier design firms who work on the same scheme of projects for a single main contractor was evaluated based on their submitted BIM capability summaries and evidence during selection process. A Fuzzy-TOPSIS framework was designed to allow objective assessment based on the adopted 28 BIM pre-qualification and selection criteria as well as weighted importance from the survey of BIM practitioners on projects in phase 1. The predicted performance based on the Fuzzy-TOPSIS evaluation was then used to rank the design firms in order of the most BIM capability. Their actual performance was also assessed based on project team evaluation of their performance in four areas namely: delivery of BIM on schedule, on budget, to specification (as stipulated in Employers Information Requirements (EIR)) and the level of collaboration on the project. The rank orders from these evaluations were then compared. The research framework is presented in **Figure 1** with the methods of analysis explained in the next section.

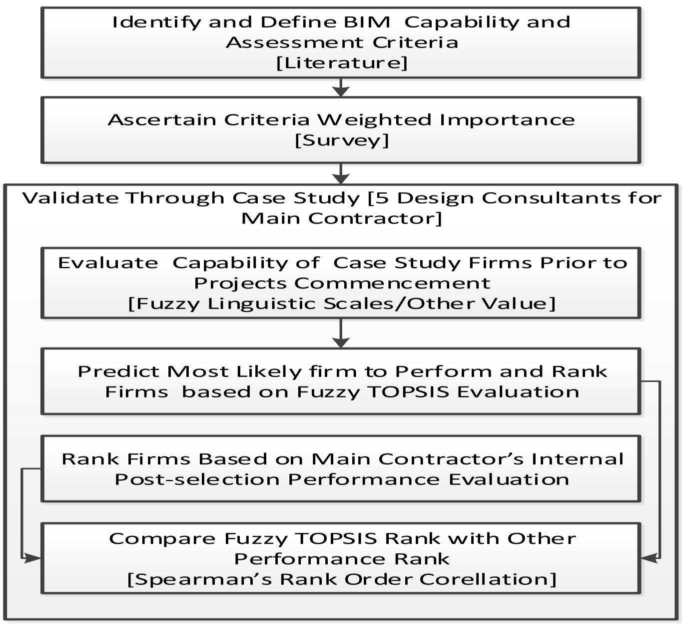

Figure 1: Research Framework

BIM Capability Criteria for Pre-Qualification and Selection

The 28 BIM qualification criteria adopted from Mahamadu et al., (2017) is organised in three-tier hierarchy consisting of four main criteria categories and eleven second tier criteria with the 28 being sub-criteria in the last tier of the hierarchy. The main categories are: 'competence' for knowledge, skills and experience in the delivery of BIM; 'capacity and resources' representing the availability of internal process maturity including physical, technical resources and a demonstration of capacity to deliver BIM specifically for project; 'culture and attitude' for attributes that indicate appropriate BIM culture and willingness to deliver BIM; and finally the 'cost' charged to deliver BIM. The eleven main BIM qualification criteria were: Qualification, Staff Experience, Organisation Experience, Administrative and Strategic Capacity, Technical (Physical) Resources, Specific BIM Modelling Capacity, Proposed Method, Reputation, Technology Readiness, Organisational Structure, and Cost. The rest of the criteria and descriptions is presented in Table 1. The 28 criteria are published and represent BIM capability assessment criteria focussing on selection and pre-qualification stage rather than generic maturity and capability in most other studies (Succar, 2009; van Berlo *et al.,* 2012; CIC, 2013b; Kam *et al.,* 2013; Giel and Issa, 2014).

Table 1: Proposed BIM Capability Criteria adopted in Study

BIM Qualification Criteria	Criteria Description	Evidence
Professional and Academic Qualifications: The organisation and staff have relevant BIM professional and academic qualifications?		
Key Technical Staff BIM Qualification	Do technical staffs possess relevant professional and academic qualifications (Degrees, Accreditations, and Certifications)?	CVs; Certificates; CPIx forms
BIM Staff Availability for Project	Can an adequate number of qualified and competent personnel be deployed specifically for the project being tendered for?	
Organisation's BIM Accreditations and Certifications	Does organisation hold any formal certifications indicating their BIM capability, maturity, and competence, standards (Licenses, Accreditations and Certifications from bodies such as Autodesk, Building Research Establishment (BRE) etc.)?	
Organisation's BIM Training Arrangements	Are there internal training programs and plans that ensure continuous improvement in BIM skills and knowledge?	
Staff Experience: The organisation demonstrate requisite levels of BIM skills and knowledge from historical/previous use or implementation of BIM?		
Managerial Staff BIM Experience	Do managerial staffs possess skills and knowledge requisite to lead BIM implementation? (evidence of leadership, PM, workflow management, administration and research and development (R&D) competencies from past use of BIM)	CVs; Testimonials; CPIx form
Key Technical Staff BIM Experience	Do technical staffs possess skills and knowledge requisite to implement BIM? (evidence of technical, operational, implementation, competencies and hardware and software maintenance and use)	
Organisation's Experience: The organisation demonstrates successful historical use or implementation of BIM?		
BIM Software Experience	Is there evidence of familiarity with requisite BIM software within the firm?	RFQ; CPIx
Past BIM Project Experience	Has the organisation previously delivered a project's successfully through BIM?	
BIM Experience on Similar Project	Has the organisation previously delivered a project of similar nature (type, size and location) successfully through BIM?	
Internal Use of Collaborative IT Systems	Is there evidence of familiarity with integrated collaborative IT systems that support a common data environment? (e.g. cloud collaboration, ERP, extranets and intranets)	
Administrative and Strategic Capacity: Is there evidence of effective vision, planning, development and management of resources in BIM implementation within organisation?		
IT Vision and Mission	Does the organisation have a vision and mission with accompanying goals on strategic use of construction IT to achieve superior performance within their organisation?	RFQ, BEPs; CPIx
Quality of BIM Implementation Strategy	Is BIM implementation within the organisation based on best practice? (i.e. policies, procedures, documentation and regulations)	
BIM Research and Development	Does the organisation have strategies to support continuous innovation, learning and improvement based on evidence or formal research within their organisation?	
Technical (Physical) Resources: The organisation has the physical technological resources and equipment for BIM?		

Software Availability	Does organisation possess appropriate BIM software licences and packages on their IT systems?	RFQ, Company BIM Capability Summaries, Licences; CPIx
Data Storage	Is there an adequate and secure data storage arrangement within the organisation that can support centralised and safe BIM or other data storage? (e.g. hardware, cloud service subscriptions and servers)	
Network Infrastructure	Is there an adequate and secure network infrastructure that can support BIM or centralised data exchange? (e.g. cloud and network bandwidths)	
Specific BIM Modelling Capacity: The organisation has specific expertise or process maturity directly related to the generation of BIM deliverables (i.e. models or data)?		
BIM Standards	Are the standards for BIM modelling and data exchanged aligned with industry standards? (PAS1192:2-5, ISO, Quality plans, Digital Plan of Works etc.)	RFQ; Company BIM Capability Summaries and BEP, Licences; CPIx
Data Classification and Naming Practices	Are data classification and naming practices aligned with best practice? (E.g. use of UNICLASS, PAS and model element breakdown structures etc.)	
Model Maturity Capacity	Does process maturity within the firm support object-based, model based or network based integration?	
LOD/LOI Capacity	Does process maturity within firm support an adequate level of development of information definition? (e.g. expertise from LOD 100-500 or use of Model view definitions and Information delivery manuals)	
Proposed Method: Is tender response or proposed method for BIM delivery adequate in meeting project specifications or client's requirements?		
Suitability of Proposed BIM Execution Plans (BEP) for Project	Is there evidence that proposed BEP will meet project BIM specifications or Employers Information Requirements (EIR)? (model review and quality assurance processes, responsibility matrices, Project Implementation Plans (PIP), Task Information Delivery Plans (TIDP), Master Information Delivery Plans (MIDP))	Project BEP (i.e. according to PAS1192; CPIx BEPs) ; CPIx
BIM Vendor Involvement and Support	Does the firm have any existing contracts, after-sales and R&D arrangements with BIM/ software/hardware vendors that will benefit project?	
Reputation: The organisation has a reputation for BIM delivery performance?		
Performance on Past BIM Projects	Are previous clients satisfied with candidate's BIM delivery performance? (E.g. testimonials, references etc.)	References; Testimonial; and CPIx
Technology Readiness: Is there appropriate culture and attitudes towards BIM?		
Attitude Towards New Technology/Willingness	Has the organisation demonstrated willingness to use innovative technologies including BIM / Is there a culture of readiness for change?	Interviews; Premise visits; CPIx
Awareness of BIM Benefits	Has the organisation demonstrated an awareness of BIM benefits in the project context? Is there evidence that this has been achieved on previous projects?	
Extent of IT Support to Core Business and Processes within Firm	Has the organisation demonstrated a culture or preference for technology oriented processes in their daily operations?	
Organisational Structure		
Organisational Structure - Level of Decentralisation	Is the organisational structure in the candidates firm open, flat or dynamic? Is decision taking adequately decentralised?	Interviews; Premise visits; Organograms
Cost		
Cost/Price of BIM Service	How much is being charged to deliver the BIM service? (For traditional selection this is usually based on lowest cost or closeness to project estimate/budget. However, for success prediction rely on the highest acceptable cost).	RFQ; Tender/Negotiated Pricing

BEP-BIM Execution Plans (Organisation/Project); CPIx-Construction Project Information Committee Protocols: CPIx A-BIM Assessment Form, CPIx B- Supplier IT assessment form; CPIx C- Resource Assessment Form (CPIc, 2013; PAS1192:2013, 2013); RFQ –Bespoke request for qualifications/proposals.

Determination of Weighted Importance of BIM Capability Criteria Weighted Importance

The contribution of BIM qualification criteria to delivery success was used as basis for prioritising criteria through allocation of weightings. This was computed through a summation of their mean perceived influence on the delivery success of the projects surveyed. Giel and Issa (2015) similarly used this method to assess priority weightings for BIM competency assessment criteria in their development of a BIM framework for owner organisations. This approach is based on a summation of the mean scores of each variable relative to the summation of means for all variables (Xia and Chan, 2012). Thus, it provides a percentage weight of criteria based on the mean rating as well as in relation to the means of other criteria. This was achieved through the equation proposed by Xia and Chan (2012) and Giel and Issa (2015) as presented in **Equation 1**. Respondents provided a performance assessment of their project organisation and teams in relation to the level of attainment of BIM success on their respective projects. In order to apply Equation 1, the questionnaire design incorporated five-point likert scale responses to which respondents rated the contribution of each capability criteria from 'Not Influential at all = 1', 'Slightly Influential =2', 'Quite Influential =3', 'Very Influential =4', to 'Extremely Influential =5'.

Equation 1: Weighted Mean Contribution

$$W_i = \frac{u_i}{\sum_{i=1}^{n} u_i} \quad (1)$$

Where:

W_i = the weighted proportion of the assessment score used for a particular BIM capability attribute;

u_i = the mean importance rating of a particular BIM capability attribute; and

$\sum u_i$ = the summation of all mean importance ratings evaluated.

Evaluation and Comparison of Post-Selection Performance of Firms

Evaluation of capability for prediction of likely performance of firms was achieved through an assessment model based on the proposed 28 criteria, the weights generated from survey and Fuzzy extension of the Technique for Order Performance by Similarity to Idea Solution (TOPSIS) method. Hwang and Yoon (1981) developed TOPSIS for ranking of alternatives based on a measure of the Euclidean distance from best scenario. Thus, it considers the best alternative as that nearest to the most ideal (positive ideal solution) and farthest from the most undesirable (negative ideal solution) (Wang and Elhag, 2006). A number of studies within construction management have relied on TOPSIS for ranking alternatives in decision making including the ranking of firms based on performance for the purpose of selecting the most suitable firm (i.e. Jato-Espino et al., 2014). The TOPSIS method consists of the following steps (Shyur and Shih, 2006; Dağdevirena et al., 2009):

Step 1: Establish a decision matrix for the ranking the firms being evaluated as follows (**Equation 2**):

$$D = \begin{matrix} & F_1 & F_2 & \cdots & F_j & \cdots & F_n \\ A_1 & f_{11} & f_{12} & \cdots & f_{1j} & \cdots & f_{1n} \\ A_2 & f_{21} & f_{22} & \cdots & f_{2j} & \cdots & f_{2n} \\ \vdots & \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ A_i & f_{i1} & f_{i2} & \cdots & f_{ij} & \cdots & f_{in} \\ \vdots & \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ A_j & f_{j1} & f_{j2} & \cdots & f_{jj} & \cdots & f_{jn} \end{matrix} \quad (2)$$

where A_j denotes the alternatives (firms) *j, j* = 1, 2, . . . ,*J* ; F_i represents *i*th attribute or criterion, *i* = 1, 2,. . . , *n,* related to *i*th alternative firm; and f_{ij} is a crisp value, which shows the corresponding rating of each alternative firm A_i with respect to each qualification criterion (F_j).

Step 2: Calculate normalized decision matrix ***R*** (= [r_{ij}]). Where r_{ij} is expressed as follows (**Equation 3**):

$$r_{ij} = \frac{f_{ij}}{\sqrt{\sum_{j=1}^{n} f_{ij}^2}} = 1, 2, \ldots .J; \; i = 1, 2, \ldots ..n \quad (3)$$

Step 3: Compute the weighted normalized decision matrix by multiplying the normalized decision matrix by corresponding qualification criteria weight which in this case was the criteria from the survey of survey (**Equation 4**):

$$V_{ij} \;=\; w_i \times r_{ij}, \quad j = 1,2, \ldots .J; \quad i = 1,2, \ldots \ldots n, \tag{4}$$

where w_i represents the weight of the i^{th} criterion.

Step 4: Determine the positive and negative-ideal solutions with **Equations 5** and **6** as expressed below:

$$A^* \;=\; \{v_{1,}^* \; v_{2,}^* \ldots \ldots v_i^*\} \\ = \left\{ \left(\max_j v_{ij} \middle| i \in I' \right) , \; \left(\min_j v_{ij} \middle| i \in I'' \right) \right\}, \tag{5}$$

$$A^- \;=\; \{v_{1,}^- \; v_{2,}^- \ldots \ldots v_i^-\} \\ = \left\{ \left(\max_j v_{ij} \middle| i \in I' \right) , \; \left(\min_j v_{ij} \middle| i \in I'' \right) \right\}, \tag{6}$$

Where I' represents benefit criteria and I'' represents cost criteria.

Step 5: *N*-dimensional Euclidean distance is then used for determination of separation distance. The positive-ideal solution $\left(D_J^*\right)$ is expressed as (**Equation 7**):

$$D_J^* \;=\; \sqrt{\sum_{i=1}^n \left(v_{ij} - v_i^*\right)^2} \;\; j = 1,2, \ldots \ldots, j. \tag{7}$$

While the negative- ideal solution $\left(D_J^-\right)$ is expressed below (**Equation 8**):

$$D_J^- \;=\; \sqrt{\sum_{i=1}^n \left(v_{ij} - v_i^-\right)^2} \;\; j = 1,2, \ldots \ldots, j \tag{8}$$

Step 6: Finally, calculate the closeness to the ideal solution for each alternative and rank based on their closeness. The relative closeness of the alternative A_j can be expressed as (**Equation 9**):

$$CC_j^* = \frac{D_j^-}{D_j^* + D_j^-} \;, j = 1,2, \ldots \ldots, j, \tag{9}$$

Where CC_j^* is an index value between 0 and 1, with the closest to 1 being the best firm.

Fuzzy Extension of TOPSIS: Despite the advantages associated with TOPSIS, there remain a few limitations with respect to its ability to deal with uncertainty and imprecision associated the subjectiveness that may be associated with allocation of scores to alternatives (i.e. firms) (Tan et al., 2010). The use of crisp values for the judgment of alternatives is sometimes problematic in view of decision maker's inability to easily assign crisp values for comparison judgments (Chan and Kumar, 2007). It has been argued that the interval judgments are easy to apply in comparison judgements, as a result of challenges in assigning a single crisp numeric value. It is also challenging to measure subjective criteria with crisp values. Another challenge is the difficulty in modelling subjectivity including ambiguity, uncertainty and vagueness associated with measuring subjective criteria. This can, however, be catered for with the incorporation of principles from Fuzzy Set Theory to mathematically model and reduce subjectivity (Zadeh, 1965).

In classical set theory, the membership of a set is dependent on bivalent condition (Zadeh, 1965). This means elements either belong to this set or not. However, Zadeh's (1965) Fuzzy Set Theory in contrast to this, allows the gradual assessment of the membership of elements in a set. Membership is described by a function valued in the real unit interval [0, 1] (Nguyen, 1985; Wang and Elhag, 2006). When this principle is incorporated into decision modelling it allows decision-makers to incorporate vagueness including information that cannot be easily measured or incomplete (Tan et al., 2010). Thus, the incorporation of fuzzy sets theory with TOPSIS is primarily to deal with such related challenges of imprecision and vagueness in judgements that are based on crisp values (Wang and Elhag, 2006; Onut and Soner, 2008).

The evaluation model adopted for the evaluation of the case study firms relied on a triangular fuzzy number in Fuzzy-TOPSIS for judgement of capability of each of the five design firms in relation to each of the 28 BIM qualification criteria. Triangular fuzzy number regarded as intuitively simple to use as well as easy to understand (Dağdevirena et al., 2009). Triangular fuzzy numbers have also been widely used as a result of the ease with which it models subjective and imprecise decision problems (Chang et al. 2007). The basic definitions of fuzzy as presented by Wang and Chang (2007) and Zimmerman (1996) was adopted and shown below:

Definition 1. $\tilde{A}$ is a fuzzy set within a universe of discourse *X* considered as a membership function $\mu_{\tilde{A}}(x)$ which associates with each element *x* in *X*, between a real number interval [0, 1]. The function $\mu_{\tilde{A}}(x)$ represents the grade of membership of *x* in in the fuzzy set.

Definition 2. A triangular fuzzy number $\tilde{a}$ can be defined by a triplet (a_1, a_2, a_3) as shown in **Figure 2**. The membership function $\mu_{\tilde{a}}(x)$ is defined as (**Equation 10**):

$$\mu_{\tilde{a}}(x) = \begin{cases} 0, & x < a_1 \\ \frac{x-a_1}{a_2-a_1}, & a_1 \leq x \leq a_2 \\ \frac{x-a_3}{a_2-a_3}, & a_2 \leq x \leq a_3 \\ 0, & x > a_3 \end{cases} \quad (10)$$

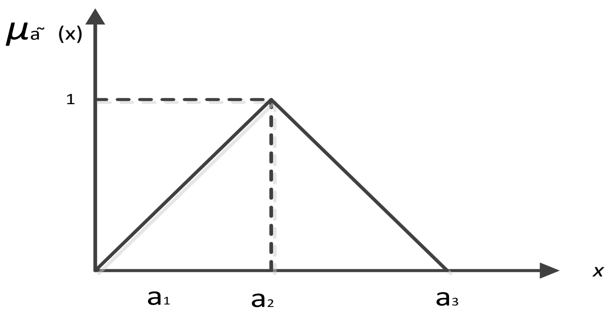

Figure 2: Triangular fuzzy number $\tilde{a}$

Let $\tilde{a}$ and $\tilde{b}$ be two triangular fuzzy numbers parameterized by the triplet (a1, a2, a3) and (b1, b2, b3), respectively, then the operational laws of these two triangular fuzzy numbers are as follows:

$$\tilde{a}(+)\tilde{b} = (a_1, a_2, a_3)(+)(b_1, b_2, b_3) = (a_1 + b_1, a_2 + b_2, a_3 + b_3), \quad (11)$$

$$\tilde{a}(-)\tilde{b} = (a_1, a_2, a_3)(-)(b_1, b_2, b_3) = (a_1 - b_1, a_2 - b_2, a_3 - b_3), \quad (12)$$

$$\tilde{a}(\times)\tilde{b} = (a+1, a_2, a_3)(\times)(b_1, b_2, b_3) = (a_1.b_1, a_2.b_2, a_3.b_3), \tag{13}$$

$$\tilde{a}(/)\tilde{b} = (a_1, a_2, a_3)(/)(b_1, b_2, b_3) = (a_1/\ b_3, a_2/b_2, a_3/b_1), \tag{14}$$

$$\tilde{a} = (ka_1, ka_2, ka_3). \tag{15}$$

Definition 3. A linguistic variable can be used as a scale for measurement in favour of crisp numbers (Zadeh, 1975). Examples of a linguistic variable for 'BIM culture' could be very poor, poor, good and very good or very antagonistic, antagonistic, collaborative and very integrated. These variables can then be represented by fuzzy numbers or membership functions. Examples of the linguistic scales for adopted for evaluating the case study firms is presented in **Table 2.**

Definition 4. Let $\tilde{a} = (a_1, a_2, a_3)$ and $\tilde{b} = (b_1, b_2, b_3)$ be two triangular fuzzy numbers. The vertex method for computing the distance between them can be expressed as follows:

$$d(\tilde{a}, \tilde{b}) = \sqrt{\frac{1}{3}\ [(a_1 - b_1)^2 + (a_2 + b_2)^2 + (a_3 - b_3)^2]} \tag{16}$$

$$\tilde{V} = [\tilde{v}_{ij}]_{n\times j} \quad i = 1,2, \dots .n, j = 1,2, \dots ., j, \tag{17}$$

Where

- $\tilde{v}_{ij} = \tilde{x}_{ij} \times w_i$
- A set of performance ratings of A_j $(j = 1,2, \dots .j)$ with respect to criteria c_i $(i = 1,2, \dots .n)$ called $\tilde{X} = \{\tilde{x}_{ij}\ ,\ i = 1.2. \dots ., n, J = 1, 2, \dots .., J\}$
- A set of importance criteria w_i $(i = 1,2, \dots .n)$.

Based on Fuzzy Set Theory, Dağdevirena *et al.* (2009) summarises the steps for Fuzzy-TOPSIS as follows:

Stage 1: Choose linguistic values $(\tilde{x}_{ij,}\ i = 1,2, \dots .., n, J = 1,2, \dots ..J)$ for each alternative (i.e. case study firm) in relation to each criterion under consideration (i.e. BIM qualification criteria). Normalisation is not necessary because the fuzzy linguistic rating $(\tilde{x}_{ij,})$ preservers the property of normalized triangular fuzzy numbers in the range [0, 1].

Stage 2: Calculate the weighted normalized fuzzy decision matrix.

Stage 3: Identify positive-ideal (A^*) and negative ideal (A^-) solution. The fuzzy positive-ideal solution $(FNIS, A^*)$ and the fuzzy negative-ideal solution$(FNIS, A^-)$ (**Equations 18 and 19**).

$$A^* = \{\tilde{v}_1^*, \tilde{v}_2^*, \dots \dots \dots \tilde{v}_i^*\} = \left\{\left(\begin{matrix} max \\ j \end{matrix}\quad v_{ij} | i \in I'\right) \times \left(\begin{matrix} min \\ j \end{matrix}\quad v_{ij} | i \in I''\right)\right\},$$

$$i = 1,2, \dots, n \;\; j = 1,2, \dots J, \tag{18}$$

$$A^- = \{\tilde{v}_1^-, \tilde{v}_2^-, \dots \dots \dots \tilde{v}_i^-\} = \left\{\left(\begin{matrix} max \\ j \end{matrix}\quad v_{ij} | i \in I'\right) \times \left(\begin{matrix} min \\ j \end{matrix}\quad v_{ij} | i \in I''\right)\right\},$$

$$i = 1,2, \dots, n \;\; j = 1,2, \dots J, \tag{19}$$

Where I' is associated with the benefit criteria and I'' is associated with cost criteria.

Stage 4: Calculate the distance of each alternative from A^* and A^- as expressed below (**Equations 20 and 21):**

$$D_j^* = \sum_{j=1}^{n} d\left(\tilde{v}_{ij}, \tilde{v}_i^*\right) j = 1,2, \ldots, J \quad (20)$$

$$D_j^- = \sum_{j=1}^{n} d\left(\tilde{v}_{ij}, \tilde{v}_i^-\right) j = 1,2, \ldots, J \quad (21)$$

Stage 5: Calculate similarities to ideal solution (**Equation 22**):

$$CC_j = \frac{D_j^-}{D_j^* + D_j^-} \quad j = 1,2, \ldots J. \quad (22)$$

Stage 6: Rank alternatives (i.e. case study firms) based on their distance from ideal situation. Maximum CC_j^* being the best and with the rest following in descending order.

Implementation of Fuzzy-TOPSIS: Fuzzy-TOPSIS relies on the provision of importance weightings to criteria. In this study the weightings for each of the 28 criteria as determined from the survey of BIM-enabled projects was incorporated into the Fuzzy-TOPSIS computation as depicted in **Figure 3**. The survey is reported in more detail in the subsequent section.

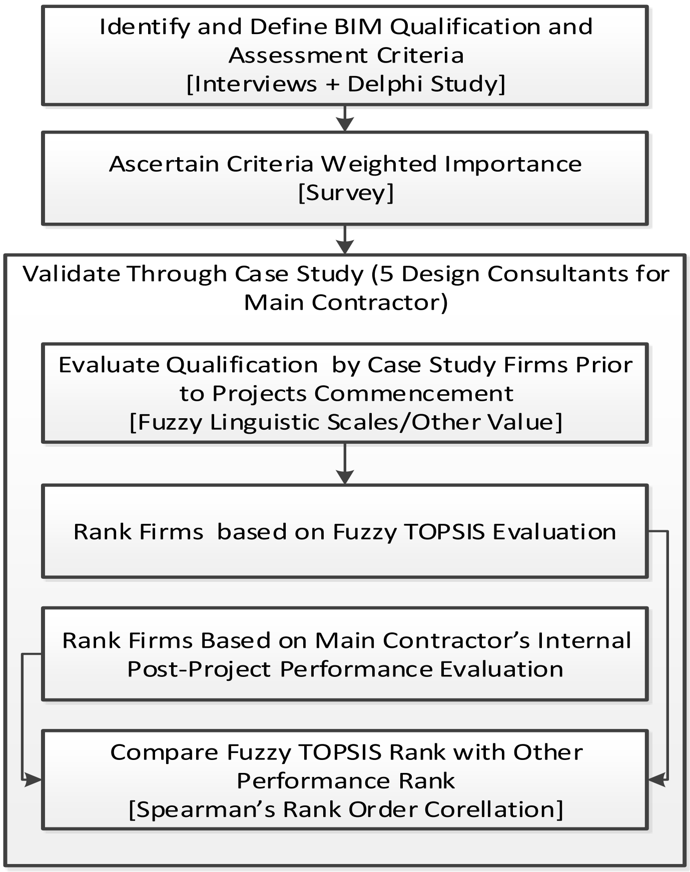

Figure 3. Schematic diagram of proposed model for evaluation of BIM capability for prediction of performance of firms in case study

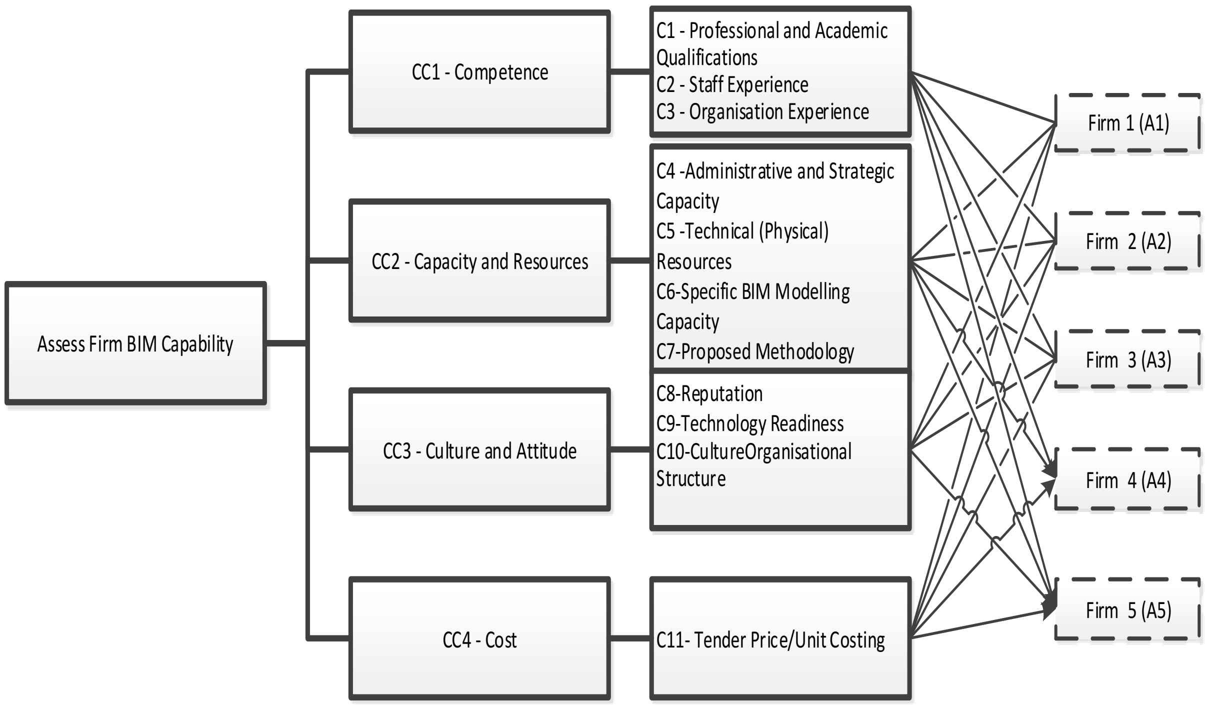

Figure 4. Decision hierarchy for selection of BIM competent suppliers

It is generally preferable for decision-makers to rate alternatives based on linguistic scales as opposed to crisp values. However, the objective criteria remain crisp such as cost or number of years' experience. The scales adopted for rating of organisations' capability level for each its capability criteria is presented in Table 2. This comprised of a six-point (0-5) scale with corresponding membership functions for the Fuzzy-TOPSIS evaluation as shown **Figure 5.**

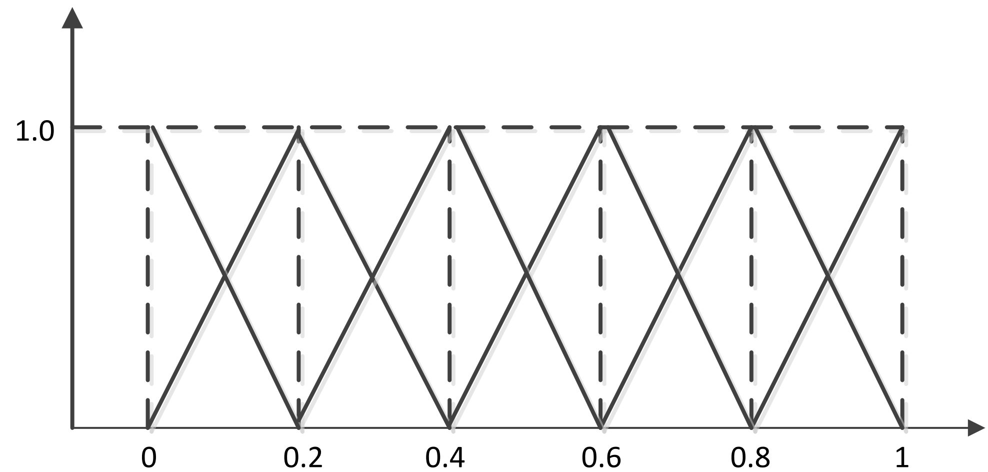

Figure 5. Membership function of linguistic values for rating criteria in Fuzzy-TOPSIS stage

Table 2: Linguistic values for subjective judgements of alternatives in Fuzzy-TOPSIS stage

Level	Linguistic Value for Subjective Judgements		Fuzzy Number	Scoring Guide Used for Assessments
V1 {0}	Very Poor	VP	(0,0,0.2)	Price charged for BIM services unacceptably low or higher (beyond) budget or client ability. No BIM processes, standards, infrastructure and functions have been defined nor currently exist. No acceptable level of knowledge, skills or evidence of practical application. There is evidence of prejudice, distrust or scepticism about digital technology and processes. Proposal did not comply and insufficient information provided to demonstrate ability to deliver to requirements or specification.
V2 {1}	Poor	P	(0,0.2,0.4)	Price charged for BIM services was far below preliminary estimate with major concerns of ability to deliver BIM at that price. BIM processes and functions are poorly controlled and reactive. Outputs are inconsistent. Equipment and technical infrastructure is generally inadequate or of low specification. Industry standards are recognised but inconsistently applied to BIM processes. There is only a fundamental understanding of BIM knowledge and skill areas. Digital technology is not well recognised as part of organisations processes. Proposals satisfied some specified requirements and specifications but not adequately.
V3 {2}	Average	A	(0.2,0.4,0.6)	Price charged for BIM services was below (10%) preliminary estimates but acceptable. BIM processes and functions are mainly on project basis and often reactive. Outputs are inconsistent but traceable. There is evidence of solid conceptual understanding and some practical application of BIM tasks. Digital technology is recognised but not formally defined as part of organisational processes. Proposals satisfied the specified requirements or specifications to a large extent but not completely.
V4 {3}	Good	G	(0.4, 0.6,0.8)	Price charged for BIM services was within at least 10% of preliminary estimate. BIM processes and functions characterised for organisation and proactive. Outputs are consistent. Significant conceptual knowledge and practical experience in performing BIM tasks. Digital technology is recognised as part of organisational processes. Proposals satisfied the specified requirements and specifications.
V5 {4}	Very Good	VG	(0.6,0.8,1)	Price charged for BIM services was above initial project estimate but within client's budget, contingency or willingness to pay. BIM processes and functions are measured and controlled. Outputs are consistent and predictable . Significant levels of knowledge, refined level of skills and practical experience. Digital technology is key to organisations processes. Proposals satisfied the specified requirements and specifications with some added value.
V6 {5}	Outstanding	O	(0.8,1,1)	Price charged for BIM services was highly above initial preliminary estimate, but within client's budget, contingency or willingness to pay. BIM processes, standards and functions are institutionalised and continuously improved Extensive knowledge, experience and refined level of skills. Digital technology is highly diffused into organisations culture and way of work with degree of automation of task. Proposals satisfied the specified requirements and specifications with exceptional added value.

*NB: the scales used in evaluation range from 0-5 {V1=0, V2=1, V3=2, V4=3, V5=4, V6=5}. *The corresponding fuzzy numbers for each scale as used in computation is presented in table*

After the Fuzzy-TOPSIS evaluation, the CC_j^* was used to rank the firms in the order of the most BIM capable firm in the group. The evaluation was based on evidence of their capability prior to selection. This ranking was then compared to ranking of firms based on project teams evaluation of performance during and after project based on the following variables: BIM delivery on schedule, BIM delivery on budget, extent to which requirements (EIR) were met. The rank from project team evaluation of performance was compared to the ranking from the Fuzzy-TOPSIS evaluation. Spearman's rank correlation was applied to ascertain if the comparison had any statistical significance. Spearman's coefficient normally denoted by *rho* or *ρ* is a non-parametric test for statistical dependence between two variables (Field, 2005; Jamieson, 2004). It compares the medians of these variables, thus, making it a preferred option for correlation analysis of ordinal data (Field, 2005).

The case study approach was adopted for the post-selection evaluation because it is most suited for in-depth exploration of phenomenon within their natural setting (Manu et al., 2015; Yin, 2013). Thus in order to do a detailed capability and performance evaluation in a typical construction project scenario, case study approach was relied on as methodology for evaluating post-qualification performance. Consequently, data was obtained through structured interviews following an assessment form based on the adopted criteria, criteria definitions and the rating scales proposed in from the Fuzzy-TOPSIS framework. Furthermore, case study approach, has been applied and proposed for in-depth evaluation of BIM implementation effectiveness and performance (Barlish and Sullivan, 2012). Despite the widely quantitative research design, the case study validation allowed for in-depth analysis of multiple sources of data that provided the relevant breadth which would not have been realised in survey or quantitatively focussed study (Yin, 2013). The case study approach allowed researchers to explain into detail the approach for evaluation of firms applying the definition of capability assessment criteria as well as how it fits the Fuzzy-TOPSIS evaluation framework. This can ordinarily not be achieved by a general survey.

RESULTS AND FINDINGS

The results and findings are presented in this section. Firstly, the results from the survey relating to criteria importance (weightings) is presented followed by the validation of criteria importance from case study and Fuzzy-TOPSIS evaluation.

Survey Participant and Project Background

The survey resulted in 13.3% response rate from an estimated survey population of 480 professionals computed based on Creative Research Systems (2003) formula. The majority of survey respondents were BIM Managers (31.4%) with a substantial proportion possessing between 11-15 years industry (46.7%) or 4-6 years BIM/VDC (35.9%) experience. In the literature, response rate of 20-30% is common with most questionnaire surveys in the construction industry (Akintoye, 2000). In construction management community that rates of 20-25% are deemed acceptable (Root and Blismas, 2003). In BIM research, a detailed survey among close to 5,500 of its registered BIM vendors, a response rate of 12% to the survey was considered excellent and acceptable (Khemlani, 2007). Thus in the case of this study a response rate of 13.3% is acceptable. In relation to academic qualifications 42.2% of respondents were holders of a Bachelor’s degree as their highest with a substantial number of postgraduate degree holders (Masters - 29.7% and Doctorate - 7.8%). This is indicative of substantially experienced and knowledgeable group of respondents. Most of the organisations assessed as part of the survey belong mainly to the top or middle tier of the project supply chain. The majority were Design Consultants, with Architects representing 34.4%, while Engineering Consultants represented 25% of the organisations assessed. In relation to the background of projects assessed, 19.3% were large scale with estimated project values above £50 million. The majority of projects (80.7%), were less than £50 million in value, more than half were above £25 million. Most of the projects (40.3%) were regarded by respondents as intermediate in terms of the level of integration of the supply chain (i.e. through coordinated strategic partnering). There was, however, a substantial number of projects (35.5%) considered to have highly fragmented (very loosely coupled firms working on one-off basis). The projects assessed in the survey were mostly building projects (90.3%).

Weighted Importance of BIM Capability Criteria (Survey)

Capacity and Resources criteria had the highest weights (42.93%), with the next being *Competence* (36.82%), followed by *Culture and Attitude* (16.75%) and lastly *Cost* (3.49%). The main BIM qualification criteria with the highest weighted contribution were *Specific BIM Modelling Capacity* with an overall contribution of 15.01% followed by *Organisation's Experience* (14.89%). The other high contributors were *Professional and Academic Qualifications* (13.43%). With regards the sub criteria, *Key Technical Staff BIM Experience* (4.60%) emerged with highest global contribution followed by *Suitability of Proposed BIM Execution Plans for Project* (4.21%).

Table 3: BIM Capability Criteria Weighted Importance for Pre-qualification and Selection

Critical BIM Capability Criteria			Mean	Survey - Weighted Importance of Criteria – Wi (%) (n=64)				
				Local	Global	Local	Global	
Capability Criteria		Constituent Attributes						
CC1 -Competence	C1 -Professional and Academic Qualifications	Key Technical Staff BIM Qualification	2.938	23.95	3.22	36.48	13.43	36.82
		BIM Staff Availability for Project	3.344	27.26	3.66			
		Organisation's BIM Accreditations and Certifications	2.391	19.49	2.62			
		Organisation's BIM Training Arrangements	3.594	29.3	3.94			
	C2 -Staff Experience	Managerial Staff BIM Experience	3.563	45.88	3.90	23.09	8.5	
		Key Technical Staff BIM Experience	4.203	54.12	4.60			
	C3 - Organisation Experience	BIM Software Experience	3.656	26.90	4.00	40.43	14.89	
		Past BIM Project Experience	3.594	26.44	3.94			
		BIM Experience on Similar Project	3.016	22.18	3.30			
		Internal Use of Collaborative IT Systems	3.328	24.48	3.64			
CC2 -Capacity and resources	C4 - Administrative and Strategic Capacity	IT Vision and Mission	3.156	31.56	3.46	25.51	10.95	42.93
		Quality of BIM Implementation Strategy	3.594	35.94	3.94			
		BIM Research and Development	3.250	32.50	3.56			
	C5 -Technical (Physical) Resources	Software Availability	3.500	38.03	3.83	23.48	10.08	
		Data Storage (suitability and capacity)	2.828	30.73	3.10			
		Network Infrastructure Availability	2.875	31.24	3.15			
	C6 - Specific BIM Modelling Capacity	BIM Standards	3.625	26.45	3.97	34.95	15.01	
		Data Classification and Naming Practices	3.500	25.54	3.83			
		Model Maturity Expertise/Capacity	2.891	21.09	3.17			
		LOD/LOI Expertise/Capacity	3.688	26.91	4.04			
	C7 - Proposed Methodology	Suitability-BEP's for Project	3.844	61.04	4.21	16.06	6.90	
		BIM Vendor Involvement and Support	2.453	38.96	2.69			
CC3 -Culture and Attitude	C8 - Reputation	Reputation -Performance on Past BIM projects	2.453	100.00	2.69	100.00	2.69	16.75
	C9 - Technology Readiness	Attitude Towards New Technology/Willingness	3.359	33.39	3.68	65.75	11.02	
		Awareness of BIM Benefits	3.734	37.11	4.09			
		Extent of IT Support to Core Business and Processes within Firm	2.969	29.50	3.25			
	C1- Organisational Structure	Organisational Structure (Level of Decentralisation)	2.781	100.00	3.05	18.18	3.05	
CC3/C11 - Cost		Cost/Price of BIM Service	3.188	100.00	3.49	100.00	3.49	3.49

Validation of BIM Capability Criteria Importance through Fuzzy-TOPSIS Case Study

The proposed fuzzy-TOPSIS evaluation model is applied in assessing the pre-selection capability prediction of design firms in a main contractor's supply chain working on the same scheme of projects (A1, A2, A3, A4 and A5) within the UK. The projects were mainly education projects costing between £10 to £25 Million. This phase was performed by a carefully selected project team who also relied on summaries of self-assessment by each of the firms in the case study. The evaluation team consisted of 10 expert evaluators with an average of 19 years construction and 6 years BIM experience. These 10 experts were invited out of a population of 15 construction professionals identified as having BIM experience and familiar with firms evaluated either as consultant or researcher. They consisted of two project managers, three architects, one quantity surveyor, two engineers and two BIM researchers with three having additional responsibilities as BIM managers. The design firms evaluated as part of the case study were mainly architectural [A1, A2, A3, A5] as well as mechanical and electrical (M&E) [A1, A4 and A5]. Evaluations were supported by the definitions of the 28 qualification criteria with assessment aided by the linguistic scales and crisp numbers (scores) for objective criteria. The capability evaluation and final judgement for each firm is summarised with respect to the eleven main criteria as presented in **Table 4**.

Table 4: Summary of agreed evaluation of case study firm performance (A1, A2, A3, A4 and A5)

Criteria	Summary of Firm Capability Evaluation										*Wi	Objective Criteria Unit
	Linguistic Value for Subjective Criteria					Numerical Equivalents						
	A1	A2	A3	A4	A5	A1	A2	A3	A4	A5		
C1	O	VG	O	G	G	6	5	6	4	4	0.134	
C2	40	35	15	25	40	40	35	15	25	40	0.085	Years
C3	6	4	3	4	2	6	4	3	4	2	0.149	Years
C5	O	VG	A	O	O	6	5	3	6	6	0.109	
C6	VG	O	A	G	O	5	6	3	4	6	0.101	
C7	A	G	O	G	G	3	4	6	4	4	0.150	
C8	P	G	O	O	O	2	4	6	6	6	0.069	
C9	G	VG	G	A	VG	4	5	4	3	5	0.027	
C10	A	A	O	VG	G	3	3	6	5	4	0.110	
C11	G	P	P	G	G	4	2	2	4	4	0.031	
C12	G	G	O	A	VG	4	4	6	3	5	0.035	
For $A*$ and A^- : $\tilde{v}^*_{C1-C11}$= (1,1,1) and $\tilde{v}^-_{C1-C11}$= (0,0,0) *Wi from Table 3.												

The fuzzy decision matrix resulting from the evaluation sores from **Table 4** was then constructed with each variable converted to corresponding fuzzy membership function. Upon developing the fuzzy decision matrix, the fuzzy weighted decision matrix is then developed (Fuzzy-TOPSIS steps 3 to 4) and presented in **Table 5**.

Table 5: Weighted fuzzy decision matrix for validation case study

Criteria	$D_j^* = \sum_{j=1}^{n} d\left(\tilde{v}_{ij}, \tilde{v}_i^*\right) j = 1,2,\ldots,J$					$D_j^- = \sum_{j=1}^{n} d\left(\tilde{v}_{ij}, \tilde{v}_i^-\right) j = 1,2,\ldots,J$				
	A1	A2	A3	A4	A5	A1	A2	A3	A4	A5
C1	0.875	0.893	0.875	0.920	0.920	0.126	0.110	0.126	0.084	0.084
C2	0.915	0.926	0.968	0.947	0.915	0.085	0.074	0.032	0.053	0.085
C3	0.851	0.901	0.926	0.901	0.950	0.149	0.099	0.074	0.099	0.050
C4	0.898	0.913	0.956	0.898	0.898	0.103	0.089	0.047	0.103	0.103
C5	0.920	0.906	0.960	0.940	0.906	0.082	0.095	0.044	0.063	0.095
C6	0.940	0.910	0.860	0.910	0.910	0.065	0.093	0.141	0.093	0.093
C7	0.986	0.959	0.936	0.936	0.936	0.018	0.043	0.065	0.065	0.065
C8	0.984	0.978	0.984	0.989	0.978	0.017	0.022	0.017	0.012	0.022
C9	0.956	0.956	0.897	0.912	0.934	0.048	0.048	0.103	0.090	0.069
C10	0.982	0.994	0.994	0.982	0.982	0.019	0.008	0.008	0.019	0.019
C11	0.979	0.979	0.967	0.986	0.972	0.022	0.022	0.033	0.015	0.028
D_j^* / D_j^-	10.286	10.314	10.323	10.320	10.301	0.733	0.703	0.689	0.695	0.711

Subsequently, the similarities to an ideal solution (CC_j) is computed and used to rank firms as shown in **Table 6** and Figure 6. The Fuzzy-TOPSIS ranks represents the ranking of firms based on assessment of capability and prediction of their likely performance. This is compared to their ranking based on project team evaluation of their actual performance. The aggregated actual performance was based on delivery of BIM models on schedule, on budget, to specification (as stipulated in EIR) and the level of collaboration on the project. The ranking of both are then compared with the aid of Spearman's correlation coefficient (ρ).

Table 6: Comparison Between Fuzzy-TOPSIS results and Project Team Ranking of Case Study Firm Performance

Case Study Firm	Fuzzy-TOPSIS (*CCj*) – Rank	Post-Selection Performance - Rank
A1	1	1
A2	3	2
A3	5	4
A4	4	5
A5	2	2
	Correlation between Fuzzy-TOPSIS Rank and Actual Performance ($\rho = 0.872$, $p < 0.05$, n=5)	

Figure 6

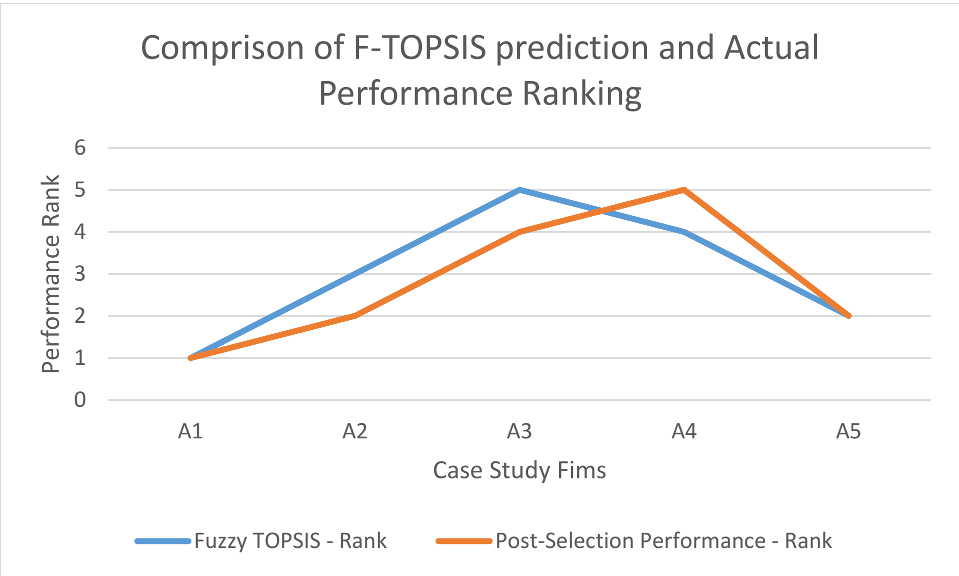

Figure 6. Comparison of Fuzzy-TOPSIS prediction and actual performance ranking of firms

Based on the results shown in **Table 9** and **Figure 7,** Firm A1 emerged as the most likely to succeed as well based on Fuzzy-TOPSIS prediction and also emerged as the best performing design firm post selection. Similarly, A5 emerged as second most likely to succeed from the Fuzzy-TOPSIS evaluation and also emerged as 2nd best performing. A2 emerged the third from the Fuzzy-TOPSIS ranking though tied on the 2nd rank in terms of post-selection performance. Based on this ranking it is unsurprising that spearman's correlation revealed strong correlation between Fuzzy-TOPSIS predictions based on capability assessment and actually post-selection performance of the firms evaluated ($\rho = 0.872$, $p < 0.05$). Correlation is measured using values between +1.0 and - 1.0. Correlations close to 0 indicate little or no relationship between two variables, while correlations close to +1.0 (or -1.0) indicate strong positive (or negative) relationships (Spiegel and Stephen 2008). Based on this finding it is clear that the 28 qualification criteria proposed as well as their weightings can reliably be used to predict the likelihood of success on BIM projects.

DISCUSSION OF FINDINGS

Based on the findings, an alternative hierarchal structure of BIM capability criteria importance is proposed and validated. The most important BIM capability criteria category for the pre-qualification or selection assessments emerged as *Capacity and Resources* followed by *Competence.* The most important of the eleven main BIM capability assessment criteria areas, *were Specific BIM Modelling Capacity* followed by *Organisation's Experience,* then *Professional and Academic Qualifications*. Overall, finding is consistent with the reliance on technological management factors in determining BIM capability in many precious frameworks (Succar, 2010; NIBS, 2012). However, the findings highlight the importance of historical and evidential demonstration of competence through knowledge and skills in BIM delivery within organisations. Furthermore, information processing related maturity (*Specific BIM Modelling Capacity)* emerged as a critical criterion for predicting likelihood of organisational BIM performance on project a finding consistent with Succar's (2009) notion of BIM capability and maturity. The emergence of *Organisations BIM Experience* as one of the most critical BIM qualification criteria aligns with the general view of contractor and consultant selection theories, where past experience is often regarded as the single most important qualification criteria (Hatush and Skitmore, 1997; Doloi, 2009). Many existing capability frameworks relate to internal implementation and benchmarking, thus often focusing on process maturity or technological infrastructure availability to the detriment of historical indicators of capability (Chen et al*.,* 2014). However, in the pre-qualification and selection context, it has emerged that a demonstration of prior experience with BIM is mostly critical to qualification. These findings are consistent with both BIM capability theories which have alluded to the importance of historical indicators of competence, (Succar et al., 2013) hard technology centric BIM maturity theories (NIBS, 2012; Sackey 2014). The role of *Managerial Staff BIM Experience* is also highlighted in this study. Despite the recognition of management buy-in as the most important criterion in BIM competence assessment (Giel and Issa, 2014), the focus on management has never been looked at from the perspective of the management's BIM experience, instead it has been looked at from a perspective of strategy (Succar, 2012; CIC, 2013b) and buy-in (Giel and Issa, 2015). From these findings, it can be concluded that design firms selection should be based on objective evaluation of their BIM capability with specific attention to evidence on their experience from past projects. Whereas this was more difficult to ascertain in the past, the evolution of BIM is now more advance with may more projects haven adopted the process (NBS, 2016) thus there are opportunities for design organisations to show their experience.

BIM Qualifications relate to the possession of externally validated evidence of capabilities and competencies. This includes certificates, licenses or degrees for individual staff or an organisation as a whole. While these have been acknowledged in the BIM capability literature (Succar et al., 2013), this study highlights its particular importance in a pre-qualification and selection scenario. Since qualification often happens within limited timescales (Holt et al., 1994; Arslan et al., 2008), the thoroughness of capability assessment can sometimes be impaired. Thus, from the findings, the possession of evidence from recognised third party institutions about an individual's or firm's ability to deliver BIM is particularly important to the qualification process.

Another finding in this study is the fact that despite the acknowledgement of the importance of *Technology Readiness* to delivery success, *Culture and Attitude* related criteria were generally less important as compared to *Competence* or *Capacity and Resources* related criteria. This is contrary to Sebastian and van Berlo's (2010) assertions which prioritises culture and attitudinal criteria as more important.

Finally, the use of cost as a qualification criterion aligns with the CIC's BIM implementation guide for evaluation of proposals (CIC, 2013b). This study further investigates the role of cost of BIM services highlighting its lack of importance as assessment criteria. This is consistent with contemporary views in construction selection, where value consideration is becoming more important than price in the selection of project participants (Holt *et al.,* 1994; Nieto-Morote and Ruz-Vila, 2012). From the findings, higher fees charged did not have a significant effect on the delivery performance of organisations. Furthermore, aligns with the view that BIM process quality is regarded as superior to price considerations in the selection of organisations to be part of the supply chain of BIM projects in Netherlands (Papadonikolaki *et al.,* 2015).

CONCLUSION

The problem of selecting BIM competent firms to be involved on BIM project teams plays a critical role in determining performance on construction projects in recent times. Consequently, construction stakeholders must, adopt the most efficient and effective methods for identifying the most appropriate organisations among alternatives available for projects. With the advent of BIM, there is a need for an evolution towards evaluation methodologies that incorporate indicators of organisations ability to deliver BIM. Despite the proliferation of frameworks and proposed capability assessment criteria, there is a lack of understanding of the relative importance of such criteria. This study has addressed this gap by proposing weightings for prioritising 28 BIM capability assessment criteria. The reliability of predicting likely success of firms using these criteria is also tested in an evaluation of firms in a real-life case study. A systematic and robust approach is proposed for validating criteria usefulness as well as importance using fuzzy-TOPSIS methodology. 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 collective information processing maturity, knowledge, skills, attitudes and experience from previous application of BIM.

Implications for practice

The main implications of the findings are discussed in relation to organisations BIM capability development, procurement and tendering. In relation to organisations development, there is a clear outline of which criteria contribute most to overall BIM delivery performance. Based on the priority weightings of qualification criteria, design firms can perform self-assessment or rely of proposed criteria for internal benchmarking for the purposes of performance management (Succar, 2009; Kam et al., 2014) or for assessment of their suitability to tender for projects (Mahamadu et al., 2017; BS EN

ISO 19650). This invariably allows organisations to identify areas of strength and deficiency in respect of their BIM capability. Given the fact that high cost of implementation remains a barrier of BIM adoption (Barlish and Sullivan, 2012), knowledge of priority areas will help in prioritisation of investments in BIM capacity building.

In relation to procurement and tendering, standards such as the PAS1192:2013 (now BS EN ISO 19650) as well as the British Standard Institute's PAS 91:2013 all require assessment of BIM capability though a methodology for assessment is not proposed. Thus the proposed assessment framework which relies on a Fuzzy-TOPSIS computational approach will aid organisations in terms of a practical and robust methodology for evaluation as well as monitoring of post-selection performance. This extends remits of previous which have only proposed critical criteria for assessment of BIM capability. These standards are adopted worldwide thus the proposition of method to fulfil one of their key objectives is a step towards more streamlined BIM implementation on projects. This has potential for reducing project cost by way of the eliminating the risk of appointing firms who are actually incapable of performance. According to Succar (2010) selection of BIM capable firm reduces the risk of failure as well as well as cost since less capable firms may include the risk of failure and their lack of capacity in their costing.

Implications for future research

In order to address scope and methodological limitations, future research could adopt entirely qualitative approaches to investigate the phenomenon of post selection performance including the use of ethnographic studies for in-depth understanding of the soft issues. Future quantitative studies may also adopt other modelling techniques, such as Artificial Neural Networks (ANN), in order to compare predictive performance versus actual performance.

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