Development of a Decision Support Framework to Aid Selection of Construction Supply Chain Organisations for BIM-Enabled Projects

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DECLARATION

This work or any part thereof has not previously been submitted in any form to the University or to any other body whether for the purpose of assessment, publication or for any other purpose. Save for any express acknowledgements, references and/or bibliographies cited in the work, I confirm that the intellectual content of the work is the result of my own efforts and no other person.

ABSTRACT

With the emergence of Building Information Modelling (BIM), a critical criterion for the qualification of a suitable Construction Supply Chain (CSC) for projects is the ability of individual organisations to deliver through the use of BIM. Despite emerging research on BIM capability assessment, there are very few studies which look specifically at the qualification (pre-qualification and selection) of CSC organisations for projects. Furthermore, there is a general dearth of knowledge about the links between often pre-emptive qualification criteria and actual delivery success, particularly, in the BIM or CSC context. This research identifies the most relevant BIM qualification criteria for CSC organisations, as well as investigating their relative importance and influence on various aspects of BIM delivery success.

A sequential exploratory mixed method research strategy was adopted in a three-phase design. The first phase explored BIM expert views on appropriate BIM qualification criteria in the UK, through interviews with BIM specialists (*n*=8). The next phase consisted of two rounds of a Delphi study with experienced construction practitioners (*n*=30 and *n*=25) to ascertain the most critical among the BIM qualification criteria derived from the first phase. This was achieved through statistical determination of Delphi participant consensus with the inter-rater agreement (r_{wg}) test. The final phase involved a survey of practitioners on BIM-enabled projects in the UK (*n*=64) in order to empirically establish the relationship between the critical BIM qualification criteria and various dimensions of BIM delivery success in practice. This was achieved through survey respondents' independent appraisal of CSC organisations on recent projects in relation to quality of BIM deliverables, delivery of BIM within schedule and on budget, plus collaboration, coordination and integration of project CSC through BIM. Various multivariate statistical analysis techniques including correlation analysis, mean weighted contribution analysis, multiple regressions modelling and analysis of variance (ANOVA) were engaged to identify qualification criteria influence on success. A decision support framework (DSF) was developed and proposed, based on the coefficients and weightings computed from the inferential statistical analysis of survey data. The research findings and DSF were validated through convergence analysis, as well as elicitation of expert respondent feedback to ensure adequacy, suitability and relevance in practice.

The findings highlight the multi-dimensional nature of the relationship between BIM capability and various elements of delivery success. It is surmised that individual BIM capability attributes influence various aspects of BIM delivery success to different extents and this must be taken into consideration when selecting CSC candidates. BIM *'staff experience'* and the '*suitability of proposed methodology'* prior to BIM project commencement were identified as the most influential criteria on BIM modelling success (quality of BIM models, delivery of BIM within schedule and on budget). Individual competencies were found to be most influential on modelling quality and delivery of BIM within budget while execution planning adequacy influenced ability to deliver BIM on time. On the other hand, the '*administrative and strategic'* level capacities were found as the most influential in relation to leveraging BIM to achieve project CSC objectives namely, collaboration, coordination or integration on projects. From a consolidation of the findings, a DSF is proposed for prioritisation of CSC organisations based on their propensity to succeed in the delivery of BIM. The work also provides an enhanced guidance on the relationship between various dimensions of BIM capability and delivery success, as well as how this knowledge enhances the prediction of CSC candidate propensity to succeed at the pre-qualification and selection phase of construction projects.

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LIST OF ABBREVIATIONS

AEC	Architecture Engineering and Construction
AHP	Analytical Hierarchy Process
ANN	Artificial Neural Network
ANP	Analytical Network Process
BEACON	Benchmarking and Readiness Assessment for Concurrent engineering
BEP	BIM Execution Plan
BIM	Building Information Modelling
BIMCS	Building Information Modelling Cloud Score
BIMe	BIM Excellence
BIMSCAT	BIM Owners Competence Assessment Framework
BIS	Department of Business and Innovation
BS(I)	British Standards Institute
CICa	Construction Industry Council
CICb	Computer Integrated Construction
CIFE	Center for Integrated Facility Engineering
CMM	Capability Maturity Models
CPIC	Construction Project Information Committee
CSC	Construction Supply Chain
CSCMM	Construction Supply Chain Maturity Model
DSS	Decision Support System
DSF	Decision Support Framework
DST	Decision Support Framework
EIR	Employers Information Requirement
IFC	Industry Foundation Class
IT	Information Technology
IU	Indiana University

JIT	Just-In-Time
MCDM	Multi-criteria Decision Support Methodologies
NBIMS	National Building Information Model Standard
NBS	National Building Specifications
MIDP	Master Information Delivery Plan
NIBS	National Institute for Building Sciences
NN	Neural Network
PAS	Publicly Available Specification
PIP	Project Implementation Plan
PM2	Project Management Process Maturity
RFI	Request for Information
RFQ	Request for Qualification
RM	Responsibility Matrix
SCCS	Supply Chain Capability Summary
SCM	Supply Chain Management
SEI	Software Engineering Institute
SPICE	Standardized Process Improvement for Construction Enterprise
TIDP	Task Information Delivery Plan
TQM	Total Quality Management
VDC	Virtual Design and Construction
VERDICT	Verify End-user E-readiness using a Diagnostic Tool (VERDICT)

DEDICATION

This thesis is dedicated to my parents, my siblings and my entire family, for their unflagging support and love throughout my life.

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

Building Information Modelling (BIM) is recognised as a vital collaborative information technology that could assist Construction Supply Chain (CSC) in achieving integrated practice (Vrijhoef, 2011; BIS 2013a; 2013b). This is expected to be achieved through centralised digital exchange of data to eliminate current information flow inefficiencies that contribute to poor performance (Arayici *et al.,* 2012). BIM is, therefore, increasingly becoming a prerequisite for construction projects, yet wider uptake of BIM across project supply chain remains a challenge due to varying levels of capability or even willingness to use it among other reasons (Gu and London, 2010; Succar *et al.,* 2012). There is a significant risk of failure if the CSC selected for projects lacks the ability to operate within a BIM environment as well as the capacity to adopt the processes and related technologies. Ample evidence demonstrates the need for metrics in evaluating organisations' ability to deliver BIM as well as attain BIM success amidst a lack of a standardised and accepted approach for establishing these (Succar *et al.,* 2012; Haron, 2013).

Despite the proliferation of frameworks and toolsets for evaluating BIM performance of firms, there remains a lack of a specifically tailored approach to predicting a firm's propensity to succeed in the delivery of BIM during the pre-qualification and selection stage. In order to address this, there is a need for the identification of qualification criteria that can be used in assessing a CSC organisation's ability to deliver through BIM. Furthermore, there is a need for a deep understanding of the contribution of such criteria to the successful use of BIM. Despite the growing number of studies on BIM capability evaluation, there remains a lack of studies specifically tailored for CSC pre-qualification or selection. Furthermore, no studies have identified the relationship between the mostly pre-emptive qualification criteria and BIM delivery success in the CSC context. The relevance of this cannot be overemphasised at a time that the UK Government expects up to 33% cost reduction, 50% time reduction and 50% reduction in greenhouse gas emissions on all projects with the wider implementation of BIM across the CSC central to the attainment of these targets (BIS, 2011; 2013a). The services delivered by the various segments of the CSC accounts for up to 80% of the value of projects; thus the use of BIM for their effective coordination and management will impact on the attainment of the UK Government strategy performance targets (BIS, 2013a; 2013b) and invariably the wider attainment of project success (Robson *et al.,* 2014).

1.2 THE NEED FOR BIM IN THE CONSTRUCTION SUPPLY CHAIN

A typical construction project is delivered through an amalgam of firms rather than a single homogeneous unit, to the extent that the industry's structure has been referred to as a loosely coupled system (Egan, 1998). The recent proliferation of subcontracting practice has further exacerbated the already fragmented structure as the production of goods and services evolves further downstream to smaller organisations in a delivery chain (Vrijhoef, 2011). According to Tardif, Murray and Associates, on the average, a construction project of an estimated value of $10 million dollars will typically involve up to 400 different organisations and 850 individuals in the delivery process (Eastman *et al.,* 2008). These firms are referred to as the CSC, a concept borrowed from the manufacturing industry to explain the complex interactions between disparate organisations involved in the delivery of infrastructure and facilities (Pryke, 2009). The structure of the CSC is, however, characterised by communication bottlenecks and lack of collaboration, resulting in process inefficiencies that contribute to a serious lack of performance (Mohamed, 2003; Briscoe and Dainty, 2005).

A critical contributor to this inefficiency is the lack of effective management of information in often information-intense construction project environments (Xue *et al.,* 2010). According to Atkin (1995), a typical construction project (valued between £5-350 million) may generate between 30,7500 to 446,500 pieces of information, including drawings, revisions, contracts, tender, variations and site instructions. The generation, transmittal and storage of such large volumes of information across diverse stakeholders and participants remain one of the most challenging aspects of managing construction. The loose coupling creates functional silos within the various organisations who often keep individualised libraries and databases of information. Zhao and Ding (2010) argue that poor quality of information management results in poor project predictably which consequently affects quality, timely delivery and budget.

According to Khalfan and McDermott (2007), the fragmented nature of the CSC has necessitated calls for an integrated approach to working where information management is facilitated by centralised information systems. The functional separations between the key construction life cycle phases (design, production and operation) and consistent reconstitutions of teams for every new project (temporary organisation) underscores the need for effective systems that facilitate data management, particularly the storage and reuse of information or knowledge (Dainty *et al.,* 2001; Khalfan and McDermott, 2007).

BIM promises a revolution in the way projects are run providing a single digital platform for all CSC communications and information management (Khalfan *et al.,* 2015). The benefits of such a system include real time information availability and access to early decision taking, reduction in lead-time and accountability (Dainty *et al.,* 2001; Mohamed, 2003). However, the establishment of a system to facilitate such inter-organisational communication is a challenging task as firms try to develop the necessary capabilities to improve their utilisation capacity (Succar *et al.,* 2012).

1.3 BIM CAPABILITY WITHIN CONSTRUCTION SUPPLY CHAIN

Despite an increase in the level of BIM usage within the industry, evidence still points to a slow rate of adoption across segments of the CSC as a result of varying degrees of proficiency (Robson *et al.,* 2014). To facilitate wider adoption in the UK, BIM is being mandated on projects, particularly public projects (BIS, 2011). The resultant emerging guidance documents, protocols and standards require principal suppliers (mainly main contractors and consultants in contract with client) to demonstrate that the rest of their CSC can deliver through BIM (PAS1192:2, 2013; Al-Ahbabi and Alshawi, 2015). UK government standards pre-qualification questionnaires now include a section specifically dedicated for BIM qualification (PAS 91, 2013). There is great emphasis on the CSC's BIM capability, hence, requiring principal suppliers to submit a Supply Chain BIM Capability Summary (SCCC) for each project as part of the qualification process (PAS1192:2, 2013).

Despite the need for demonstration of BIM capability there remains a lack of standardised approaches for qualifying the CSC based on their BIM capabilities. There has been a proliferation of capability, maturity, readiness and competence assessment frameworks and toolsets. Despite their development, there remains a lack of frameworks specifically tailored for cross comparative assessments during pre-qualification and selection phase. Most of the existing tools have been primarily developed to assist firms to identify priority areas affecting BIM implementation rather than qualification for projects. The existing tools are, thus, susceptible to omissions and additions which render them unsuitable for CSC pre-qualification or selection.

1.4 BIM CAPABILITY AND BIM DELIVERY SUCCESS

Project success is generally described as the attainment or exceeding of project objectives (Takim and Akintoye, 2002). This has traditionally been observed in relation to quality, cost and delivery on schedule (Takim, 2005). More recently, collaboration and integration have similarly become important success indicators particularly in relation to the CSC context (Vrijhoef, 2011). To reduce the risk of failure, qualification of construction firms must be based on prediction of the firm(s) with the highest propensity towards success (Doloi, 2009a). Thus, there is a need for knowledge about the contribution of qualification criteria to project success (Al-Zahrani, 2013).

Construction firm qualification has evolved resulting in many empirical studies investigating the relevant attributes, criteria and computational models required for selecting most suitable candidates. Many Decision Support Frameworks and Tools (DSFs/DSTs) have been developed in this regard to aid decision makers to choose the best firms out of several alternatives. This has, however, been done without significant attention to the relationships between qualification criteria and delivery success (Doloi, 2009a). With the emergence of BIM qualification as a major factor in CSC selection, there is a need for identifying critical BIM qualification criteria as well as establishing the relationship between such criteria and BIM delivery success.

Emerging standards, frameworks and tools provide basis for identifying appropriate BIM qualification criteria for selecting CSC on BIM-enabled projects (Succar, 2009; van Berlo *et al.,* 2012; NIBS, 2012; CIC, 2013b; Kam *et al.,* 2013a, b; Succar *et al.,* 2013; Du *et al.,* 2014; Giel and Issa, 2014). However, none of these initiatives provide the necessary links between BIM utilisation capacity of an organisation and delivery success particularly. 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 rather than overall project success especially in the CSC context. Therefore, while these initiatives have provided useful guidance for assessment of BIM capability in general, their application to the qualification (pre-qualification or selection) process requires further attention. Most existing tools are designed for BIM implementation or general performance assessments. Consequently, questions remain regarding their suitability as DSF's during the pre-qualification or selection process.

1.5 THE KNOWLEDGE GAP

The dearth in literature and lack of specifically tailored BIM assessment frameworks for qualification of CSC on projects leaves a significant research gap that needs to be filled. Several limitations exist in relation to the use of existing BIM capability assessment frameworks and toolsets. One of the key limitations is the fact that, most of the tools have been designed to measure capability for the purposes of BIM implementation or project performance monitoring rather than qualification or selection (Succar, 2010; Haron, 2013; Kam *et al.,* 2014). The qualification process is, however, unique and requires a more holistic, but concise approach, as well as a precise prediction of the likelihood of success. Existing capability frameworks are, however, limited in this regard.

Most of the existing tools and frameworks focus on hard measures pertaining to the physical resources and processes required to deliver BIM models as opposed to other competency factors and organisational factors (Sebastian and van Berlo, 2010; Chen *et al.,* 2016). Sackey (2014) has described BIM capability discourse as technologically deterministic to the neglect of the socio-technical nature of its use in practice. Sackey's (2014) assertions are confirmed by the multiplicity of frameworks that focus on assessing BIM as a product or technical process to the neglect of many people related attributes (see NIBS, 2007; IU, 2009; NIBS, 2012; Du *et al.,* 2014). The soft human behavioural or organisational factors that influence the competence to deliver BIM have not been adequately considered by most frameworks despite evidence of the role of these factors in BIM delivery success (Sebastian and van Berlo, 2010; Haron, 2013). There are, however, a few frameworks that have considered all these dimensions of capability (see Succar, 2010; van Berlo *et al.,* 2012; CIC, 2013b; Giel and Issa, 2014; Kam *et al.,* 2014). However, none of these were developed for the purposes of selection or for the UK CSC context. Furthermore, the complementary application of different frameworks is challenging due to the disparities in the types of evaluation criteria considered as well as their importance weighting which renders them generally incompatible (Sebastian and van Berlo, 2010).

Aside limitation related to criteria used, there are also methodological challenges as well as lack of empirical validation of most existing frameworks. Firstly, there is a relative lack of reliance on robust computational methods for prioritising criteria used in existing BIM capability frameworks (Mahamadu *et al.,* 2015). Generally, the relative importance of criteria in these frameworks has either been arbitrarily allocated or based on their contribution to BIM maturity (Succar, 2010; CIC, 2013b) rather than their contribution to delivery success. Secondly, scientific underpinning for validating most existing tools is unclear (van Berlo *et al.,* 2012; Kam *et al.,* 2013b). This is attributed to the fact that a good number of these frameworks have been developed for commercial reasons rather than for academic research purpose (Giel and Issa, 2014). Furthermore, some of these tools were developed as part of BIM implementation guidance rather than for academic purposes, thus, lack the necessary academic rigour in the determination of criteria or criteria importance (see Succar, 2010; CIC, 2013b; PAS1192:2, 2013; PAS91, 2013). Most importantly, there is no existing study that has investigated

BIM capability attributes in relation to their use as qualification criteria, as well as their influence on BIM delivery success from a UK or CSC perspective.

While the possession of BIM capability indicates ability to implement or deliver tasks (Succar, 2009), it is unclear how capability influences successful delivery of broader BIM usage objectives (success). Emerging studies have, however, only investigated the role of maturity in project performance rather than BIM delivery performance or success (Smits *et al.,* 2016). Furthermore, some of these studies have sometimes provided contradictory results regarding which BIM capability criteria are the most important (van Berlo *et al.,* 2012; Kam *et al.,* 2013b; Giel and Issa, 2014). In order to select the most suitable candidates for projects, the qualification process (pre-qualification or selection) requires detailed understanding of the relationship between various BIM capability attributes and delivery success. Thus, there remains a need for detailed understanding of BIM capability attributes, their use as qualification criteria, as well as influence on BIM delivery success. Furthermore, the identified weaknesses in existing frameworks could be addressed with the development of a more tailored approach that suits the CSC BIM qualification process with the most relevant BIM criteria.

The following research questions were posed to address the research gap.

1.6 RESEARCH QUESTIONS

The research intends to answer the following questions:

- What are the most critical BIM qualification criteria for the CSC?
- What are the relationships and contributions of qualification criteria to the successful delivery of BIM in the CSC context?

1.7 RESEARCH AIM

The study aims to examine the contribution and relationship between BIM qualification criteria and successful delivery of BIM in the supply chain context. This is to aid the proposition of a novel approach to assessing CSC firms' likelihood to succeed in the delivery of BIM on construction projects.

1.8 RESEARCH OBJECTIVES

To address the research questions and study aim, the following step-wise objectives will be addressed:

1. *To develop an understanding of BIM capability attributes, their uses as qualification criteria for the CSC, as well as their role in successful delivery of BIM in the supply chain context;*

2. *Identify and categorise BIM qualification criteria in order to develop a hierarchy of assessment criteria for CSC pre-qualification or selection purposes*;

3. *Identify the most critical criteria and prioritise them based on their relative contribution to the successful delivery of BIM*;

4. *Ascertain the impact of qualification criteria on specific BIM delivery success areas in the supply chain context of BIM use;* and

5. *Develop and validate a Decision Support Framework (DSF) to aid the pre-qualification or selection of CSC for BIM-enabled projects.*

1.9 TIMELINESS AND IMPORTANCE OF STUDY

The UK Government regards BIM as central in achieving real cultural change within an industry that has been criticised for under-achievement and inefficiency in industry reviews (Latham, 1994; Egan 1998). Government's targets include increased efficiency of delivery, improved carbon performance and up to 33% cost reduction on public projects through deployment of BIM with most of such reduction expected further down the CSC (BIS, 2011; 2013a). As part of Government's recent construction strategy, BIM has been mandated on all public projects at a minimum maturity level two by 2016 in a road map towards attainment of level three in the near future (BIS, 2011; 2013b). This study, therefore contributes to knowledge of BIM implementation success through characterisation of criteria for BIM qualification and modelling of determinants of success in the UK CSC selection process.

1.10 SCOPE OF RESEARCH

The research focus is BIM use in CSC practice in the UK. The study is of primary relevance to principal suppliers (such as clients or main contractors) who normally perform pre-qualification or selection activities prior to commencement of projects. Currently, most published and validated BIM evaluation frameworks from academic studies have been developed outside the UK. Thus there is a need for a specific framework for the UK and CSC context.

1.10.1 Key Research Terminology

The key research terminology is defined below in the context within which they have been used in this thesis.

Construction supply chain (CSC): Organisation with a role in the project delivery process right from conception through to demolition and recycling.

Principal supplier: An organisation with direct contractual relationship with a client and responsible for supervising other CSC organisations.

BIM capability: The ability to implement or deliver tasks. BIM capability in this study is therefore used broadly to represent all related concepts such as BIM maturity, BIM competence and BIM readiness.

BIM qualification: BIM qualification in this thesis is used to represent the assessment of BIM capability specifically for pre-qualification or selection purposes.

1.11 OUTLINE OF PROPOSED METHODOLOGY

Methodological pluralism, which encourages the use of multiple methodological approaches, is proposed as an appropriate research method to break the barriers of limited literature and data sources due to novelty of BIM as a research area (Creswell *et al.,* 2003; Knight and Ruddock, 2008). In this regard, a pragmatic philosophical stance is adopted and incorporates both qualitative and quantitative strategies to address the outlined objectives. Pragmatism is a widely associated paradigm for the conduct of mixed method research (Creswell, 2003). Furthermore, it focuses on adoption of the most appropriate research strategies, which answer each aspect of the research question adequately, hence its pluralistic and practical nature (Amaratunga *et al*., 2002). It, therefore, works well across both interpretive (qualitative) and positivist (quantitative) paradigms (Creswell, 2003). Moreover, as both the construction and information sciences represent a multi-disciplinary domain of interconnecting areas of specialism, it makes the identification and use of one appropriate research methodology challenging, hence the need for a balanced approach.

A sequential exploratory mixed method research strategy is adopted. The first phase explores BIM expert views on appropriate CSC BIM qualification criteria based on their experience as part of tender evaluation process in the UK. This is achieved through interviews with 8 construction BIM specialist with managerial roles in leading UK construction organisations. The interviews were used to generate a wide range of possible qualification criteria for the CSC. The interview phase was followed by Delphi survey of 30 construction practitioners with BIM experience resulting in the return of 25 valid final Delphi responses. This was used to ascertain most critical BIM qualification criteria to be used for framework development. Critical criteria were determined through statistical determination of Delphi participant consensus through the inter-rater agreement statistic (r_{wg}) with the aid of *'R'* software package.

A subsequent survey of practitioners on (n = 64) BIM-enabled projects in UK was used to establish the relationship between the critical BIM qualification criteria and delivery success. This was achieved through survey respondent's independent appraisal of CSC organisations on the surveyed projects. Various multivariate statistical analysis techniques were engaged to identify qualification criteria influence on success with the aid of SPSS 19 software. The statistical techniques employed included correlation analysis, mean weighted contribution analysis, multiple regressions modelling and Analysis of Variance (ANOVA). A DSF was developed and proposed based on coefficients and weights computed from the survey findings and multiple regression analysis. The research findings and DSF were validated through a test of agreement between the main survey and validation survey of experts as part of a convergence analysis. Another set of experts were engaged to validate the general findings and DSF in relation to adequacy, suitability and relevance in practice. Justification for the use of methods and mode of enquiry is explained in the research methodology chapter.

1.12 ORGANISATION OF CHAPTERS

This thesis consists of 10 chapters organised as indicated in Figure 1.1.

Chapter 1: In this chapter the research background is presented highlighting the relevant research gaps. The justification for the research is highlighted. This chapter includes a brief introduction of the CSC and the relevance of BIM in CSC qualification for projects, as well as gaps in knowledge. The aim and objectives as well as a general overview of methods and organisation of the thesis report are presented in this chapter.

Chapter 2: This chapter seeks to provide a general overview of the concepts of supply chain and the role of BIM in CSC discourse. An introduction to CSC concept and the role of BIM in the integration of CSC is presented in this chapter. A case for CSC BIM capability evaluation as part of their qualification for projects is made highlighting role of various UK BIM implementation guidance documents.

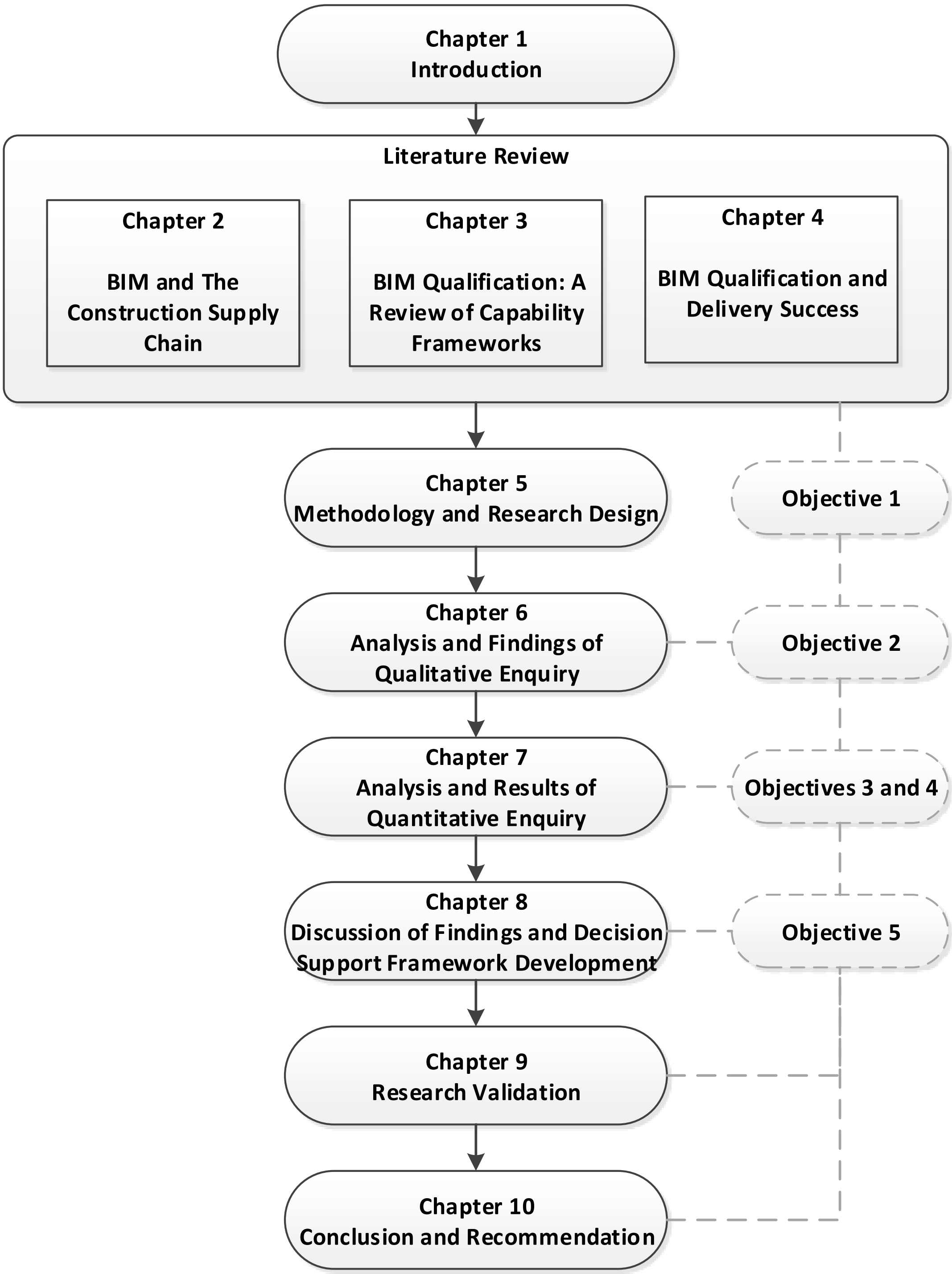

Figure 1.1: Organisation of the Chapters in the Thesis

Chapter 3: This chapter presents a review of literature on existing approaches for BIM capability and assessment. A review of existing frameworks and their use in toolsets is performed to identify relevant assessment criteria and limitations. The frameworks reviewed in this chapter include academic and professional BIM capability assessment initiatives including capability, maturity, competence and readiness frameworks.

Chapter 4: This chapter provides a definition of success in construction and its relevance during pre-qualification or selection phase. A review of previous studies investigating the impact of qualification criteria on project success is presented. The review reveals a lack of studies on the relationship between BIM qualification criteria and successful delivery of BIM especially in the CSC context.

Chapter 5: In this chapter, an outline is provided detailing the research methodology and strategies adopted for this study. A justification is provided for choosing a sequential exploratory mixed method strategy. The choice of interviews, the Delphi technique and a general survey is also justified in this chapter.

Chapter 6: Qualitative data collected from interviews exploring BIM qualification criteria is summarised and presented in this chapter. This includes a review of the approach to data analysis, a presentation and summary of the key findings.

Chapter 7: Quantitative data collected from a Delphi and general survey is presented in this chapter. This includes a review of the data analysis techniques and justification for the chosen methods. This chapter includes a presentation of results and summary of key findings from the quantitative enquiry.

Chapter 8: In this chapter, the key research findings are discussed with reference to existing knowledge and literature. The discussions draw distinctions and parallels between the current study and previous related research. The chapter further details the consolidation of the findings into a DSF to guide tender evaluators to select most suitable CSC candidates on projects. The schematic representation of the DSF including a computational framework and adopted scales to aid scoring of qualification criteria is also presented and discussed.

Chapter 9: This chapter discusses the methods adopted to ensure research validity. This includes an expert validation survey, as well as respondent feedback on the key findings and DSF.

Chapter 10: The conclusions and recommendation from this research are presented in this chapter. The contribution to knowledge is highlighted both in terms of practice and theory. Other identified but unaddressed gaps discovered in the course of the research are presented as precursor for future research in this area of study.

1.13 CHAPTER SUMMARY

A background to this research has been provided highlighting the lack of frameworks for CSC BIM qualification process for projects. A need for knowledge on the influence of qualification attributes on delivery success is highlighted. The research aim and objectives have also been presented. The next three chapters (2, 3 and 4) provide a review of literature to highlight the gap and set the tone for rest of the research.

CHAPTER 2: BIM AND THE CONSTRUCTION SUPPLY CHAIN

2.1 INTRODUCTION

This chapter presents a review of literature on the role of BIM in the Construction Supply Chain (CSC), as well as the need for assessing CSC's ability to deliver BIM during selection of candidates for projects. The literature review is in three main parts. The first part presents an overview and contextual definition of BIM. In the second part, the evolution of BIM within the UK construction industry as well as impact on the CSC management is also discussed. The review provides a general overview of the challenges related to managing the CSC and the role of BIM in alleviating these challenges. Finally, the case for BIM qualification in CSC procurement is discussed.

2.1.1 Definition of BIM

There remains some ambiguity relating to the definition and meaning of BIM. Three major distinctions can be drawn from the definitions and meanings attributed to BIM within the literature. Some refer to BIM as a software application, design and documentation of the building information process or even an entirely new approach to practice. However, one of the most widely cited is the National Institute of Building Science (NIBS) definition, which describes BIM as "a *digital representation of physical and functional characteristics of a facility and a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle*" (NIBS, 2007, p.7). According to Azhar *et al.* (2007) BIM is the development and use of a computer-generated model for planning, design, construction and the operation of a facility. The BIM model is data-rich, object-oriented, intelligent and parametric with all stakeholders having the capability to extract, analyse and generate information that can be used for decision making (Azhar *et al.*, 2007). BIM has also been described as a new approach for the description and display of information required for the design, construction and operation of constructed facilities (BuildingSmart, 2012).

The NIBS definition of BIM is adopted for this study in view of its encapsulation of the major related concepts of BIM (Gu and London, 2010). Moreover, this research examines BIM as an integrative solution for the CSC hence the need for a holistic definition. According to Eastman *et al.* (2008) and Arayici *et al.* (2011), BIM represents an embodiment of policies, processes and technologies for the integrated management of construction data throughout a facility's life-cycle. These definitions of BIM highlight the potentially expansive nature of BIM and its coverage of various digital, collaborative and integrated construction technologies.

2.1.2 BIM Implementation in UK Construction Industry

In the UK, the Government's promotion of the use of BIM in the 2011 Construction Strategy has instigated great attention to BIM within the construction sector. All public projects are expected to use BIM at maturity level two by 2016 in a road map towards universal adoption (BIS, 2011). Maturity is used to describe progressive stages in BIM implementation (Succar, 2009). The standard BIM maturity classification as stipulated in the PAS1192:2 (2013) are explained below.

BIM Stage 1 (level 0-1)

This represents the progression from unmanaged to managed Computer Aided Design (CAD), both in 2D or 3D formats. At this stage, project stakeholders are engaged with industry standards and processes such as the BS1192 in completely individualised or non-connected data and software systems (PAS1192:2, 2013). This may include stand-alone, design, engineering, communication, finance, or cost management packages (Succar, 2010).

BIM Stage 2 (Level 2)

This stage refers to the 3D model-based collaboration envisaged as the main form of data management (Succar, 2010). This will, however, be based on data produced and held in separate discipline based proprietary tools (Succar *et al.,* 2012). The standards required for their production should however allow high degrees of interoperability, object based with sufficient levels of information detail and parametrisation (PAS1192:2, 2013). Integration at this stage can be achieved through proprietary interface or bespoke middleware (Succar, 2010).

BIM Stage 3 (level 3)

This stage represents the maturity level where network-based integration is to be achieved with the aid of fully open and interoperable processes enabled by standards, such as Industry Foundation Class (IFC) (Succar, 2009). Most of the available commercial BIM software applications already possess such IFC data exchange capabilities (such as Autodesk Revit, Archicad, Vico, Bentley Micro Station), though the extent to which they are fully utilised is not clear. Data and information is managed by a collaborative single platform model server with functionality that supports every CSC discipline's data uses (PAS1192:2, 2013). The progression of BIM maturity is depicted in Figure 2.1.

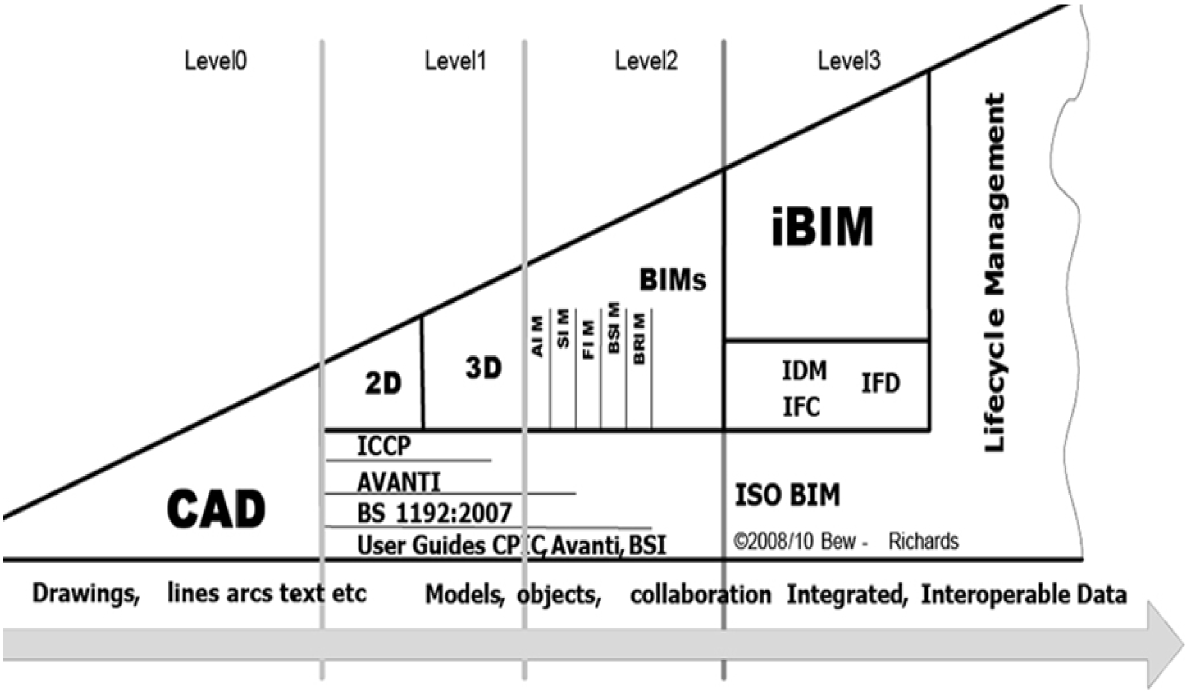

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Figure 2.1: Progression through BIM Maturity and Relevant Standards and Documentation

Adoption of level two BIM, as envisaged by Government, will require all project data to be managed in a 3D virtual environment, where individual CSC disciplines contribute or extract data with proprietary tools that have high inter-operable data exchange capabilities, that are supported by project data exchange protocol and standards (PAS1192:2, 2013). This will require the use of federated project BIM or data models, linked to individual proprietary databases or software for each

CSC discipline (BIS, 2011). The Government's aim of using BIM level two includes the expectation of performance improvements and overall improved project success rates. The targeted improvement areas include project delivery efficiency, improved carbon performance and up to 33% cost reductions (BIS, 2011; 2013a). It is expected that, BIM will stimulate these improvements as a result of its many touted benefits.

Level three maturity represents entire system integration, through single model server platforms where individual CSC contribute to projects in common or completely synchronised data environments (PAS1192:2, 2013). It is, however, envisaged that as the CSC matures (level three and beyond) in their level of BIM adoption, tighter organisational coupling and collaboration within the CSC becomes a prerequisite. This may, therefore, introduce newer organisational challenges in addition to traditional fragmented structures, which often results in functional barriers to effective information exchange (McAdam, 2010; Robson *et al.,* 2014).

Since the announcement of UK government strategy on BIM, there has been a steady rise in the level of adoption across the CSC. A survey of BIM use within UK and Europe at large, revealed 35% to 36% BIM use among respondents (McGraw-Hill, 2010). The national building specification (NBS) survey of an estimated 1350 professionals and organisations revealed that almost 39% of respondents were using BIM in UK, with 71% agreeing to the importance of BIM in future construction information management (NBS, 2011). A significant proportion (74%) of respondents, however, alluded to the prevalence of a lack of clarity about how to implement BIM effectively (NBS, 2011). BIM adoption is generally believed to be led by architects, followed by engineers and contractors (McGraw-Hill, 2010; 2012; 2014) with most other CSC organisations generally perceived to be lagging behind in terms of BIM adoption (Robson *et al.,* 2014).

Based on a survey of the CSC of a major contractor in UK, Robson *et al.* (2014) reported that a quarter of respondents had used BIM with another 44% not currently using BIM at all. The latest NBS national survey (2016) (n = 1000) reports BIM adoption by 54% of respondents, up from 48% the previous year.

Majority (86%) of respondents in the latest NBS survey intend to increase BIM use within a year with 97% planning to adopt BIM in the next five years.

2.2 BIM AND CONSTRUCTION SUPPLY CHAIN

Building Information Modelling is recognised as a vital collaborative information technology that could assist the CSC in achieving integrated practice (Vrijhoef, 2011). It is expected that future project processes will be streamlined through the centralisation of communication and information flows on virtual digital platforms (Succar *et al.,* 2012). It is believed that a centralised digital exchange of data will eliminate the current information flow inefficiency that contributes to poor performance of CSC on projects (Arayici *et al.,* 2012). BIM is, therefore, increasingly becoming a prerequisite for projects. However, lack of uptake remains a challenge due to (among other reasons) varying levels of maturity, capability, competence or even willingness to use it across the CSC (Gu and London, 2010; Succar *et al.,* 2012).

A significant risk of failure remains if project participants (or the CSC) lack the ability to operate within a BIM environment. More importantly, it is also argued that for the benefits to be realised, BIM must effectively diffuse across the CSC, which accounts for the majority of activities (up to about 80% of total value) in the delivery process (Robson *et al.,* 2014). Thus, for every project, there is a need for the assessment of the CSC's ability to deliver through BIM successfully.

2.2.1 The Concept of Construction Supply Chain

The concept of the CSC originates from Supply Chain Management (SCM). Despite disputed claims over the origins of SCM, it is believed that it was pioneered as a result of the need to improve performance within the manufacturing industry through adoptions of concepts such as just-in-time (JIT) and total quality management (TQM) in the 1980's (Manu, 2014). The promotion of SCM was as a result of the realisation that strategic and cooperative supplier-buyer relationships often lead to better communication and value driven processes (Briscoe and Dainty, 2005). Furthermore, advances in business process reengineering (BPR) led to more emphasis on the redesign of operational and strategic organisational structures to reduce waste and increase efficiency (Pryke, 2009). Thus, organisational and process improvements initiatives collectively lead to developments in a management paradigm, SCM.

The International Centre for Competitive Excellence defined SCM as *"an integration of key business processes from end user through original product suppliers with the aim of providing products, services and information that add value for customers and other stakeholders*" (cited in Cooper *et al.,* 1997, p. 2).

Performance challenges also led to the adoption of SCM principles in construction. This has been on the back of industry reviews that called for improvements in productivity with more focus on efficiency through integration, teamwork and partnerships among firms in the supply and delivery process (Latham, 1994), as well as re-engineering of the construction production and organisational processes (Egan, 1998). The recommendations from these reports resulted in the promotion of project procurement structures that promote the coupling of firms in the construction delivery chain. Based on such integrative principles, the CSC needs to be designed in the form of a dynamic network of interdependent organisations that can collaborate more efficiently to satisfy the overall attainment of project goals through better co-operation and co-ordination of individual actors (Pryke, 2009).

A CSC firm is sometimes referred to as a 'supplier' and this represents any firm that contributes to the effective delivery of a project or activities of a client or a main contractor. The CSC may, therefore, include the main contractor, but is mostly used to refer to consultants, sub-contractors and other relevant service providers in the delivery process (Briscoe and Dainty, 2005).

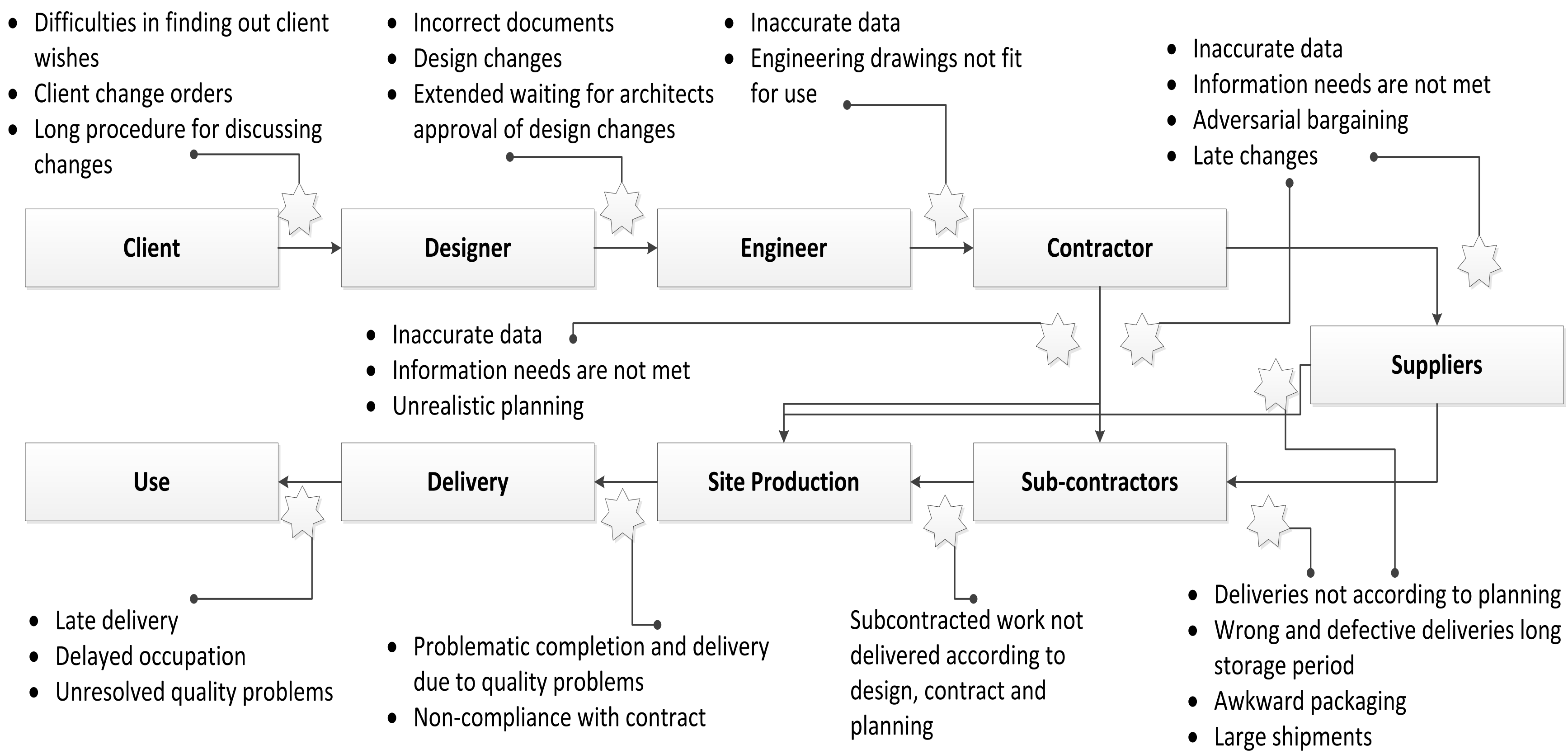
2.2.2 Fragmentation in the Construction Supply Chain

For the past 30 years, a proliferation of subcontracting practice has however increased levels of fragmentation within the CSC pushing key activities within the production process across a diverse group of small firms with varying levels of capability (Pryke, 2009). The wide variety of firms with different levels of specialist labour as well as the casualisation of workforce have exacerbated the loss of central control (Vrijhoef, 2011). Some have referred to the construction industry as a loosely coupled system rather than an industry (Egan, 1998; Briscoe and Dainty, 2005).

At the project level, a typical construction project will consist of many separate organisations operating together as a single production unit (Briscoe and Dainty, 2005). Furthermore, the configuration within most project organisations is usually disconnected with virtually two separate units, focussed on design or management and production activities respectively (Vrijhoef, 2011). The level of disconnection between design, management and production often results in conflicting goals and viewpoints which exacerbate the levels fragmentation (Khalfan *et al.,* 2007).

The most pervasive problem with the project CSC structure is inter-organisational boundaries, which often create information flow issues as depicted in Figure 2.2. The critical points where information related problems often occur are highlighted on the diagram. They include inaccurate data, incorrect documents, change, and difficulties in interpreting client requirements, non-compliance and overall poor delivery success.

The typical structure of the CSC consists of tiers or organisations with varying levels of participation and responsibility (Dainty *et al.,* 2001). The top tier often consists of organisations directly in contract with owners and clients that may include main contractors or consultants who are referred to as principal suppliers. The middle tiers often include firms directly procured by the top tier and typically include sub-contractors and consultants. The lower tiers often include firms in direct contract with the middle tier and may typically include material suppliers and manufacturers.



Source: *Vrijhoef (2011) – reused with permission from © IOS Press*

Figure 2.2: CSC Process and Information Delivery Challenges

2.2.3 Information Technology and the Integration of the Construction Supply Chain

According to Atkin (1995) a typical construction project (value between £5-350 million) may generate between 30,750 to 446,500 pieces of information including drawings, revisions, contracts, tender, variations and site instructions. Furthermore, estimations from several construction projects reveal that, projects (average value US$ 10 million) generate up to 56,000 pages of documents of vital information (Tardif, Murray and Associates (Canada), cited in Eastman *et al,* 2008, pp. 2-3). It is estimated that this is shared between 420 firms and up to 850 individuals. The generation, transmittal and storage of such large volumes of information across diverse stakeholders, therefore remains one of the most challenging aspects of managing construction. Each of the CSC organisations usually maintains a huge library requiring regular updating and management. In some cases these are maintained and managed by third party intermediaries. The information exchange process could, however benefit from recent advances in IT (Zhao and Ding, 2010; Xue *et al.,* 2012). The greatest value associated with the use of IT is the ability to allow users to develop networks beyond the borders of the individual firm boundaries for the purposes of data sharing and management (Zhao and Ding, 2010).

Many tools have emerged promoting integrated CSC communication and practices. These are often referred to as integrative or collaborative IT communication tools which may involve centralised communication either from a single IT platform or inter-communications between separate systems (Adriaanse *et al.,* 2010). This includes first generation collaboration and integration tools within construction such as intranet, extranet and enterprise resource planning systems (ERP) (Xue *et al*., 2012). Real-time information availability is therefore one of the major ways of managing an integrated CSC as it allows early decision taking, reduces lead-time and promotes accountability (Mohamed, 2003).

2.2.4 Integration of the Construction Supply Chain through BIM

The attainment of CSC integration and collaboration is regarded as panacea to the attainment of better performance as well as attainment of business and strategic objectives in the long term (Vrijhoef, 2011). The CSC has opportunities of optimising "*resources and capabilities through co-ordinated strategies within network-like structures"* (Mohammed, 2003, p.1). The importance of building such network-like structures has particularly been highlighted with the growing popularity of management paradigms which supports the integration of process, people and organisational structures (Briscoe and Dainty, 2005).

Integrated working facilitates collaboration and teamwork through structures that allow timely knowledge and information sharing, minimisation of errors, elimination of rework and the resultant time loss (Xue *et al.,* 2012). A review of recent developments highlights a growing recognition of integration as capable of delivering higher productivity and project performance. The under-performance of projects has also been attributed to lack of coordination and cooperation in an often fragmented sector (Dainty *et al.,* 2001.) The calls for integration of the CSC is consistent with a global trend in delivering industrial performance through vertical integration of supply chains across the product delivery cycle mainly within manufacturing sectors (Vrijhoef, 2011).

Zao and Ding (2010) argue that poor quality of information results in the failure to deliver projects predictably, to required quality, on time and within budget. The ethos for the paradigm shift in SCM within the manufacturing sector was the recognition of the importance of eliminating waste through lean management practices, which was widely successful within the automotive industry (Khalfan and McDermott, 2007). SCM principles recognised the integral management of suppliers as key in delivering value within the production system through centralised control and coordination of the entire delivery chain (Briscoe and Dainty, 2005). This is on the basis of the recognition of the importance of downstream suppliers whose activities often directly affect focal operations. Similarly within the construction industry, products and services are usually provided by firms further downstream the supply chain (Constructing Excellence, 2004).

BIM is recognised as a vital collaborative information technology that could assist the CSC in achieving integrated practice (Vrijhoef, 2011). The expectation is that future project processes will be streamlined through centralisation of communication and information flows on virtual digital platforms (Succar *et al.,* 2012). Centralised digital exchange of data is expected to eliminate the current information flow inefficiency that contributes to poor performance of the CSC on projects (Arayici *et al.,* 2012). According to Vrijhoef (2011), BIM can act as the integrator since the majority of the CSC's problems emanate from real time information availability and communication.

2.2.5 BIM Benefits to the Construction Supply Chain

Research on the state of the UK CSC was undertaken in 2013 by the Department for Business, Innovation and Skills (BIS) almost five years after the commencement of an extended downturn in the industry. According to the BIS (2013b) report, overall industry output (in 2012) was about 88.5% of the levels recorded during the global economic downturn (in 2008), with no expectation of real improvements in the immediate future. The performance downturn is attributable to the continued existence of fragmentation despite the wider acceptance of vertical integration on the part of main contractors who have taken over a key role of integrator and seemingly increased adoption of procurement that facilitates integration (Manu, 2014; Khalfan *et al.,* 2015).

BIM use in the UK CSC is, however, still minimal with a reported insufficient level of usage in some segments of the CSC especially in the lower tiers (BIS, 2013b). Shared usage of communication systems is expected to contribute to better coupling of highly fragmented CSC thereby increasing collaborative practice (BIS, 2013a; 2013b). Furthermore, ever increasing costs and challenges in the stabilisation of the global economy means the construction industry must adapt to austerity requirements in order to remain competitive and relevant. The estimated cumulative saving required on construction cost through BIM is between 15-33% in the UK (BIS, 2011; 2013a; 2013b).

Yan and Damian, (2008) reported the following benefits from BIM users: reduced time, need for human resource, improved quality, sustainability and creativity. Based on 400 survey responses, the NBS reported benefits including improved visualisation (85%), improved productivity due to easy retrieval of information (84%) and increased coordination of construction documents (81%), cost efficiency (61%), increased profitability (53%) and increased speed of delivery (51%) (NBS, 2011). According to the NBS national survey (2013), more than 50% of BIM adopters have reported greater cost efficiencies as a result of BIM use, with more than 70% reporting an increased level of coordination of construction documentation (NBS, 2013). Robson *et al.* (2014) reported the following benefits specifically for CSC BIM use: improve design coordination, reduce risk through identifying potential problems early on, and facilitate better communication of project data. According to the 2016 NBS national BIM survey, UK, 63% believe BIM could lead to Governments targets of up to 33% reduction in the initial and whole life cost of built assets. More than half (57%) of respondents, believe BIM can lead to up to 50% reduction in time whilst 39% were of the opinion that 50% reduction in greenhouse gas emissions can be achieved in the built environment through BIM use. Some academic studies have also reported 73% perceived increases in profitability among BIM users as against 3% perceived decrease in profitability (Becerik-Gerber and Rice, 2010).

BIM is being proposed as a solution mainly because it enhances information sharing and collaboration across multiple firms in construction projects (Succar, 2009). The BIS (2013b) analysis of the UK market, therefore, recognises the need for the use of BIM to aid the management of the following within the CSC.

• Early contractor and sub-contractor involvement in solution development, facilitated by appropriate procurement arrangements which incentivise and reward supply chain contribution (BIS, 2013a);

• Greater coordination of design and assembly across the supply chain, possibly based on BIM, recognising the disaggregated structure of the supply chain (BIS, 2013b; Robson *et al.,* 2014);

• Improved management of change, focused on reducing the opportunity costs to the industry of unmanaged change (BIS, 2013b);

• Wider adoption of the integration role of supply chain management, either at tier one or two, focused on the management and coordination of related trades in a dis-aggregated supply chain (Vrijhoef, 2011; BIS, 2013b); and

• Efficient and well-coordinated on-site operations, facilitated by integrated and settled site teams, capable site management and proportional management of change (BIS, 2013b).

Nummelin *et al.* (2011) similarly identified the following as the most salient opportunities of BIM for CSC integration: early supplier involvement and collaborative design management; better cost estimation; tendering and procurement; improved and lean site logistics and material management; and better built information data through BIM databases. Other reported BIM benefits to the CSC is presented in Table 2.1.

Table 2.1: Summary of BIM Benefits to the CSC

Category of Benefits to CSC	Description	Sources
Benefits related to increased CSC organisational efficiency	Responsiveness, timely of data transfer, reduced Request for Information (RFI) and changes, predictability and visualisation of scheduling and planning.	Ahuja *et al.* (2009); Arayici *et al.* (2012); Bryde *et al.* (2013)
Benefits related to effective use of technology	On-demand access and availability of information; flow of accurate information; reduced hard copy storage of documents/drawings	Ahuja *et al.* (2009); Suerman (2009); Barlish and Sullivan, (2012); BIS (2013b)
Benefits related to effective team management	Effective collaboration, coordination, communication and joint decision making	Hu (2008); Suerman (2009); Azhar (2011); BIS (2013b)
Benefits related to measures of project success in general	Cost and time predictability, quality and sustainable delivery	Suerman (2009); Bryde *et al.* (2013); Khalfan *et al.* (2015)
Benefits related to increased CSC organisational performance in general	Profitability, business continuity, responsiveness	Ahuja *et al.* (2009); Azhar (2011); Bryde *et al.* (2013); Khalfan *et al.* (2015)

2.2.6 Challenges to BIM Implementation in Construction

The establishment of a system to facilitate inter-organisational communication presents a challenging task due to its sheer scale and the need for congruence in the interest of participants within such a commercially driven environment (Adriaanse *et al.,* 2010; Mahamadu *et al.,* 2013a). Implementation is, therefore, still challenged by the technological complexities of BIM, as well as the human, organisational and commercial context of its usage (Gu and London, 2010). For instance, it has been reported that higher perceptions of risks exist as a result of the openness of a centralised system, which may expose valuable intellectual property (Singh *et al.,* 2011).

The challenges to BIM implementation have been widely reported. According to Newton and Chileshe (2012, pp.3-12), the most highly-ranked challenges include 'lack of understanding about BIM', 'education and training costs', 'start-up costs' and 'changing the way firms do business'. The high expectation of information sharing requires organisational interoperability. This is often regarded as a contributory factor to legal challenges and possible disputes emanating from ambiguity about data ownership, copyright and data protection (Azhar, 2011; Mahamadu *et al.,* 2013c).

Some other reported challenges include: overcoming the endemic resistance to change; changes from traditional and existing processes and task workflows; and understanding of the responsibilities of different actors in a typical project organisation (Eastman *et al*., 2008; Arayici *et al*., 2012; Navendren *et al.*, 2014). Authority and control over information involving diverse parties has been cited as a key challenge (Davies and Harty, 2013). There is also some uncertainty as to who bares the associated costs of implementation (Azhar, 2011). Some of the challenges have also been attributed to relatively low capacity, capability and extent of development of BIM-related technologies (Mahamadu *et al.,* 2013c). This includes lack of IT resources and network capability to run BIM applications competently (Eastman *et al*., 2008; Singh *et al*., 2011). Other cited challenges include lack of interoperability due to a lack of standardised approaches to sharing data across diverse proprietary information systems and software is seen as a major challenge (Gu and London, 2010).

The general unavailability of vendor-neutral data formats and standards, as well as issues regarding accessibility and security of data are challenges yet to be appropriately addressed (Singh *et al*., 2011; Mahamadu *et al*., 2013b). According to Eastman *et al.* (2008) the lack of awareness or promotion of BIM through standardised guidelines and implementation support impedes successful adoption. BIM specific requirements are yet to be adequately embedded within current procurement, contracts and legal structures in order to alleviate some of the above-mentioned challenges (McAdam, 2010). Navendren *et al.* (2014) studied a group of design consultants revealing the following categories of challenges: design-specific, team-orientated, project-related, technology related (BIM specific), industry-wide challenges and cost. The specific critical challenges for implementation of BIM included design process lag and loss of time; lack of understanding by clients regarding requirements for the BIM model; lack of learning feedback from projects on which BIM has been used; and lack of supply chain integration. Furthermore, there is lack of understanding of the tools and techniques required to deliver BIM. According to Navendren *et al.* (2014) there is also a need for process redesign to accommodate the new BIM induced procedure within CSC practice. According to Robson *et al.* (2014) the key barriers to CSC BIM implementation are as follows: vulnerability to the weakest link (where poor performance by one of the subcontractors becomes a limiting force in a set of supply chain relationships); set up costs; and (c) cultural change.

The above discussion demonstrates that there remain several challenges to BIM implementation. Many of the challenges can, however, be overcome if the CSC builds the right capability to deliver BIM.

2.3 CAPABILITY OF THE CONSTRUCTION SUPPLY CHAIN TO DELIVER THROUGH BIM

As the CSC continues to develop the necessary capabilities, the delivery of projects through BIM remains a big hurdle (Succar *et al.,* 2012). Evidence points to inconsistency in the levels of adoption due to varying degrees of proficiency across various sectors of the CSC (Giel and Issa, 2013). This is amidst a lack of standardised approach for evaluating a supplier's ability to deliver BIM, especially during the selection process (van Berlo *et al.,* 2012). The risk of failure, thus, remains where the participants (CSC) lack the ability to operate through such a medium (Beechey, 2013). Ample evidence demonstrates the need for metrics in evaluating performance especially in relation to organisational readiness, capability or competence as it aids objective benchmarking for the attainment of BIM objectives or deliverables (Succar *et al.,* 2012; Haron, 2013).

Many organisations have made claims on their ability and proficiency in delivering projects through BIM (van Berlo *et al.,* 2012). This is, however, amidst the lack of a standardised and well accepted approach to measuring the ability to deliver BIM (Succar *et al.,* 2012; Giel and Issa, 2013). There have been attempts to address the problem of assessing the ability to deliver BIM with a proliferation of capability frameworks and tools (van Berlo *et al.,* 2012). However, many of the criteria and metrics developed have specific objectives that make their applicability to other situations challenging (Giel and Issa, 2013). A review of existing frameworks and toolsets that could be used in assessing organisations' performance reveals lack of tools tailored to evaluating the CSC firm's readiness or capability during the supplier selection process. The pre-qualification or selection stage, however, remains important in the construction process as it enables contractors and clients to select the most appropriate candidates for executing projects (Mbachu, 2008).

2.3.1 BIM Qualification and the Selection of the Construction Supply Chain

A variety of BIM capability and performance evaluation approaches have been proposed to quantify BIM utilization capacity of enterprises. While these have been used to assess the level of uptake or capability, questions remain regarding their suitability for assessing qualifying firms during the pre-qualification and selection process. The existing frameworks and toolsets include capability maturity type evaluation tools developed by various industry bodies and academics for benchmarking firms in key performance areas (NIBS, 2012; Succar *et al.,* 2012). A golden standard suitable for CSC selection has, however, not emerged with the objectives of existing tools rendering most of them unsuitable as CSC qualification tools. It, therefore, still remains challenging for firms to identify measurable BIM criteria to aid comparison of the BIM proficiency of firms as well as predict their likelihood to succeed in the use of BIM on a project (Giel and Issa, 2014).

The selection process allows the determination of competent firms to participate in projects or to be qualified as part of a principal suppliers' team. The selection of suitable suppliers to be engaged on a construction project has significant effect on the success and attainment of project objectives

(Jaselskis and Russell, 1991). When selected candidates possess the required level of capabilities and competence, there is a higher chance of successful delivery on the project (Nieto-Morote and Ruz-Vila, 2012). This selection process remains one of the most critical milestones in the construction project life cycle (Holt *et al.,* 1994). There are two main activities associated with the pre-qualification or selection phase of projects. The first is usually the pre-qualification phase where a shortlist of suppliers is determined in order to invite them for a second round of selection (Plebankiewicz, 2012). The second is the actual selection phase, where suppliers are assessed in order to determine or predict the most suitable candidate to be selected as part of a CSC or project delivery process (Plebankiewicz, 2012).

In order to minimise the risk of selecting incapable suppliers, the process for evaluating alternative candidates must be methodical, thorough and complete (Holt *et al.,* 1994; Plebankiewicz, 2012). Both clients and main contractors are faced with the challenge of assessing and prioritising potential candidates as a result of the need for consideration of their capability in many relevant areas (Hartmann *et al*., 2009). An emerging core competence area for successful completion of projects is the ability to deliver through BIM (van Berlo *et al.,* 2012). Resultantly, guidance documents in the UK have recognised the need to assess the ability to deliver through BIM.

2.3.2 UK Standards and BIM Qualification

Since the publication of the UK Construction Strategy (2011), many industry standards and initiatives have been introduced to promote the use of BIM across the CSC (Figure 2.1). Standards, guidance documents and protocols have since emerged. These protocols and guidance have advocated and sometimes mandated assessment of BIM capability as part of the qualification process for CSC firms on projects. Thus, there is an increasing requirement that, firms demonstrate the ability to deliver BIM for all projects. For instance the PAS1192:2 and Construction Industry Council (CIC) protocols requires principal suppliers (main contractors or clients) to demonstrate their CSC BIM capability for projects tendered for.

The PAS 91 (2013) offers additional questions for the incorporation of assessment criteria for BIM capability on all projects to be tendered for using the UK standard pre-qualification documents. The Construction Project Information Xchange (CPIx) proposes forms for principal suppliers to demonstrate capability through provision of a summary of each supplier's ability to deliver BIM. Another key guidance document is the AEC (UK) BIM Protocol (V 2.0) (AEC, 2012). This evolved from the AEC (UK) initiative, formed in 2000 to improve the process of design information production, management and exchange. The AEC (UK) BIM Protocol (V 2.0) builds on existing protocols and standards such as the BS1192:2007(2007), PAS1192-2 (2013) and BS8541-1.

The PAS 1192-2:2013 (2013) specifies the need for a project implementation plan (PIP). This must include suppliers' IT and human resources capability to deliver the requirements of an Employers Information Requirement (EIR). A summary of such capability is expected to be delivered as part of a BIM Execution Plan (BEP) or Project Implementation Plan (PIP). This is to be submitted by the principle supplier (usually main contractor to client) and must include the capabilities of the entire CSC intended to be used on the project.

The capability of the CSC is expected to be demonstrated in the Supply Chain Capability Summary forms (SCCS). This set of forms must show human resource and IT capability and capacity of each CSC member. To aid this, the CIC BIM protocol and PAS1192-2:2013 recommends forms produced by CIPx for collecting such data. The forms consist of an IT resource, BIM assessment and general supplier assessment form. The definitions of the standard documents required for BIM project execution are presented in Table 2.2.

One of the most important documents is the EIR, which is becoming a standard requirement for each project as part of the UK BIM Level two universal implementation objectives (PAS 1192:2, 2013). The EIR is a document that details project constraints and variables driving the project BIM requirements. This includes client type, supply chain BIM competency, project type, forms of contract and the scope of works. The EIR also details what information will be required at what stages and the needed data formats under the contract for the entire CSC. While these standards and associated documents have stated some key data required to make these assessments, they provide little guidance on how individual supplier assessment can be performed. For instance, the relative importance on the criteria to be used remains the prerogative of the assessor (client and principal suppliers).

Table 2.2: Description of BIM Project Execution Documentation (PAS 1192:2, 2013, pp.8)

Recommended Documentation	Description
Employers Information Requirement (EIR)	Summary of clients BIM requirements, deliverables and expectations for project.
Project Implementation Plan (PIP)	Submitted pre-contract-award to demonstrate potential supplier's capability in relation to information management
Task Information Delivery Plan (TIDP)	Submitted by each task team that will be working on project , setting out each team's information delivery responsibility
Responsibility Matrix	A document showing the relationship between disciplines and production of information or models
Master Information Delivery Plan (MIDP)	Demonstrates all project TIDPs in relation to construction programme
BIM Execution Plan (BEP)	Submitted at pre-contract stage to address the issues raised in the Employers Information Requirement (EIR) and provide details of proposed supplier's methodology for delivering the project using BIM
Supply Chain Capability Summary (SCCS)	BIM/Supplier/Resources and Assessments Forms (i.e. CPIx). Forms used to summarise key attributes of suppliers (CSC) which demonstrates their BIM capability

As part of the responsibilities stipulated for UK BIM adoption, the CSC is recommended to use recently released standards for pre-qualification (PAS 91:2013, 2013) which includes additional questions for assessing BIM competence. Similarly, the PAS 91, only provide some relevant questions leaving actual evaluation to be done by assessors.

Since detailed BIM qualification procedures are not recommended in the implementation documents above, assessors are expected to use their subjective judgement in the allocating criteria weights. The allocation of weight to criteria in pre-qualification and selection has always been done based on experience or good judgement. However, there is a need for an evidence-based approach. According to Doloi (2009a) allocating these weights must be based on empirical evidence about the contribution of each criterion to delivery success. None of the standards nor required documentations and assessment forms (Table 2.2), however, proposes specific criteria for the CSC nor criteria weighting for the conduct of assessments as part of the pre-qualification or selection process.

2.4 CHAPTER SUMMARY

The definition of BIM, SCM and the CSM has been provided in this chapter. A case is also made for BIM qualification of the CSC for projects. The assessment of a CSC firm's ability to deliver BIM has become one of the most important aspects of construction projects. Thus, qualification criteria for projects must include the assessment of organisational attributes that contribute to their ability to deliver BIM or within a BIM environment. In the next chapter, capability assessments frameworks are reviewed to ascertain their applicability to the qualification of CSC for projects.

CHAPTER 3: BIM QUALIFICATION - A REVIEW OF BIM CAPABILITY FRAMEWORKS

3.1 INTRODUCTION

This chapter reviews the existing frameworks and other toolsets for the evaluation of the ability to deliver BIM. These are often referred to as capability assessment frameworks or tools. However, BIM capability is used to represent other related concepts such as BIM qualification, competence, performance, maturity and readiness. A variety of assessment frameworks for the above concepts have been developed by various industry bodies as well as academia. These frameworks and toolsets are reviewed to ascertain their suitability for qualifying firms during pre-qualification and selection. Definitions and conceptual propositions for BIM capability assessment is also reviewed as a precursor to identifying suitable BIM qualification criteria. The chapter, therefore, provides an overview of existing frameworks and toolsets, their objectives, criteria, strengths and limitations.

'Qualification' is often used in the pre-qualification and selection context to denote the assessment of an ability or suitability for selection (Holt *et al*., 1995; Doloi, 2009a; Sebastian and van Berlo, 2010; CIC, 2013b). Thus, in this study the term 'BIM qualification' is used to refer to the assessment of a CSC firm's ability to perform a task or deliver a BIM service or product during selection or pre-qualification. 'BIM capability' on the other hand is used to describe the ability to deliver a BIM service or product in the general sense.

3.2 BIM CAPABILITY ASSESSMENT

Despite rapid advancements in the implementation of BIM, apposite development of metrics to gauge the level of implementation is yet to be achieved (Giel and Issa, 2013). According to Kam *et al*. (2014) benchmarking of BIM implementation through performance metrics lags behind performance management in general, particularly, areas such as green building assessment (such as BREEAM and LEED) and construction safety. However, the availability of assessment methodologies for various aspects of BIM capability will enrich professional knowledge as well as accurate assessment of the market, challenges and trends (Kam *et al.,* 2013b).

The most critical areas of BIM metrics is the assessment of the ability to manage the organisational and technological processes associated with BIM adoption. The terms capability, qualification, performance, maturity, competence and readiness have all been used inter-changeably to describe this ability. According to Aziz and Salleh (2011) an awareness of capability areas aids the identification of the ability to experiment with new construction related technologies. It further supports the evaluation of the innovation diffusion process for digital technologies into organisational set-up (Khalfan *et al.,* 2001).

Without BIM capability metrics, individuals and organisations are unable to measure successes or failure in their BIM implementation (Succar, 2010). BIM metrics also allow organisations to assess the competencies they possess as well as aid the benchmarking of their performance against peers or competitors (Succar *et al.,* 2012; Kam *et al.,* 2014). This will, therefore, create appropriate feedback loops for appraisal of performance as well as identification of areas of improvement (Kam *et al.* 2013b). According to Succar *et al.* (2012) the availability of BIM capability metrics eliminates the proliferation of a 'BIM wash', where firms and individuals falsely claim to have capabilities in delivering BIM services.

3.2.1 Definition of Concepts Related to BIM Capability

In order to alleviate the challenges associated with the identification of an ability to implement BIM, Succar, developed a series of frameworks conceptualising BIM capability, maturity and competency (Succar, 2009; 2010; Succar *et al*., 2012; 2013). Succar, (2010) differentiated between capability and maturity in his model describing BIM capability as the basic ability to perform a task or deliver a BIM service, while BIM maturity refers to the quality, repeatability and degree of excellence within a BIM capability. From this description capability denotes a minimum ability, whereas maturity denotes the extent of that ability. However, these terms have been used interchangeably in BIM discourse. Succar *et al.* (2013) identifies BIM competency as a distinct assessment area in BIM capability evaluation and describe a competency set as a generic set of abilities suitable for implementing BIM. Conversely, Haron (2013) refers to the ability to deliver BIM as 'readiness' representing the degree to which an individual or organisation is prepared to obtain benefits of implementing BIM.

BIM assessment frameworks and toolsets have been developed for different scenarios including individual, team, organisation, project and even entire country-level capability assessments (Succar, 2010). Some of the strategic objectives of BIM capability assessment include: BIM performance management; BIM certification and licensing; identification of success and failure in BIM implementation; common reference point for competency or capability; easy identification of BIM goals and objectives; competency and capability reference point for academia; competency and capability reference point for training and human resource development; easy definition of BIM project requirements; and the identification of qualification criteria for pre-qualification and selection (Succar, 2010; Succar *et al.,* 2012;2013; Giel and Issa, 2013; Kam *et al.,* 2013b).

3.2.2 BIM Capability and the Qualification of the Construction Supply Chain

Despite the acknowledgment of the need for capability as part of qualifying organisations for projects (PAS1192:2, 2013; PAS91, 2013), no specific framework showing criteria priority and relationships has emerged for this purpose (Alaghbandrad *et al.,* 2015). A review of existing frameworks and toolsets is provided below with an assessment of their suitability for the pre-qualification or selection phase of projects.

The proliferation of standards and guidance documents for BIM capability has mainly targeted specific audiences or project phases. This has rendered most of them unsuitable for assessing CSC BIM capability (qualification) during pre-qualification or selection (Mahamadu *et al.,* 2015). Thus, the determination of a CSC firm's qualification for projects remains difficult. The need for assessing each constituent member of the CSC is primarily as a result of requirements stipulated in the BIM standards (see PAS1192:2, 2013). Furthermore, construction IT success is mostly dependent on the readiness of all organisations involved in the construction delivery processes rather than a single organisation (Aziz and Salleh, 2011).

3.3 A REVIEW OF BIM CAPABILITY FRAMEWORKS AND TOOLSETS

Since the objectives for the developments of existing BIM capability frameworks and tools vary, their applicability in scenarios outside the context of their development is limited. A review of developments in BIM capability frameworks and tools is presented below.

3.3.1 Capability - Maturity Assessment Frameworks and Toolsets

Capability Maturity Models (CMM) have been used to assess the quality of organisational processes within software firms since the late 1970s (Paulk *et al.*, 1993). Some of the most popular models include the quality management maturity grid by Crosby (1979) and the CMM by Carnegie Mellon Software Engineering Institute (SEI) (Paulk *et al.*, 1993). According to Eadie *et al.* (2011) maturity models are characterised by structured elements representing key process areas as well as capability stages for progressing in these process areas. Thus, a maturity model aids the identification of critical process areas responsible for a firm's performance or capability in delivering a particular function (Crosby, 1979). They are popularly used in performance management to provide guidance on steps towards improving performance in key organisational process areas.

Maturity models have been used in many domains including construction. The notable examples within construction include the Standardized Process Improvement for Construction Enterprise (SPICE) (Sarshar *et al.,* 2000). Another example is the project management process maturity model (PM) 2 for assessing an organisation's project management capability (Kwak and Ibbs, 2002). Some other models have been developed for IT related capability including the Benchmarking and Readiness Assessment for Concurrent Engineering in Construction (BEACON) and the Verify End-user E-readiness using a Diagnostic Tool (VERDICT) (Khalfan *et al*., 2001; Ruikar *et al.,* 2006). Lockamy and McCormick

(2004) also developed the Construction Supply Chain Maturity Model (CSCMM) for assessing CSC's SCM maturity and performance.

Similarly, with the emergence of BIM, the maturity modelling concept has been adopted to model BIM capability (NIBS, 2007; Succar, 2010; Giel and Issa, 2015). Succar *et al.* (2012 p. 124) defined BIM maturity as "*the quality, repeatability and degree of excellence within a BIM capability".* According to Succar (2010) BIM maturity is primarily used to benchmark performance improvement milestones (or levels) during BIM implementation. The notable BIM capability maturity frameworks and toolsets are reviewed below.

3.3.1.1 The NBIMS Capability Maturity Model (CMM)

This is regarded as one of the first attempts towards BIM performance evaluation. This tool was developed as part of National BIM Standards in the USA (NIBS, 2012). The NBIMS CMM provides a pathway for assessing the minimum requirements for a firm to successfully engage with BIM (NIBS, 2007). According to McCuen *et al.* (2012) the tool was developed for the following functions:

- Evaluate the practice and process regarding the BIM implementation;
- Provide a portfolio-wide analysis to establish an organisations level of strategic or operational implementation of BIM; and
- Aid the setting of goals for achieving greater information maturity on future BIM projects.

The tool consists of eleven key areas of assessment namely: data richness; life-cycle views; roles or disciplines; change management; business process; timeliness, response; delivery method; graphical information; spatial capability; information accuracy; interoperability and IFC support (NIBS, 2007). The NBIMS CMM is based on ten levels of maturity (on a scale of 1–10, where 10 denotes the most mature) (NIBS, 2012). The determination of final scores in the CMM matrix (criteria versus maturity) is based on weighted aggregation of all criteria. Based on these scores an assessed entity can now be graded as minimum, certified, silver, gold or platinum in BIM modelling (NIBS, 2012). Two versions of NBIMS CMM exist. The first version is based on a static Microsoft Excel workbook and the second is an interactive Microsoft Excel spreadsheet.

This tool has been validated in case studies including award winning American architectural practices (McCuen *et al.*, 2012). The key limitations of using this tool is the fact that it tends to focus on output or product (BIM model development) rather than maturity or competence of the organisational processes. The criteria relied on, therefore, is skewed since only technical BIM modelling attributes are measured. According to van Berlo *et al.* (2012) there remains a lack of global validation given that the criteria used in the CMM was based on the American context. Furthermore, the NBIMS CMM is only suitable for parts of the project team rather than an organisation as a whole. The matrix and scoring guidance for the NBIMS CMM is shown in Table 3.1.

3.3.1.2 BIM Planning Guide for Facility Owners - Pennsylvania State University - Computer Integrated Construction (CIC)

The Penn State University has developed a facility owner's guide to BIM execution (CIC, 2013b). In this document they provide guidelines for BIM maturity assessment in the form of a maturity matrix. This is to aid owner/client organisations to assess their BIM capability and implementation strategies. The matrix consists of six categories of assessment criteria. The assessment criteria used were adopted from the CIC research document on the planning elements of BIM (CIC, 2013b). The key areas of assessment are strategy, BIM uses, process, information, infrastructure and personnel. Assessments can be performed according to five stages of maturity, which represent pathways for improvement (Giel and Issa, 2015). The matrix only forms part of a broader implementation guidance note and is specifically for assessing internal BIM implementation maturity of owner organisations (CIC, 2013b). This document, however, includes guidance for qualifying organisations to be part of BIM-enabled projects through an assessment of Request for Qualifications (RFQ) and Request for Proposals (RFP).

Table 3.1: The NBIMs Capability Maturity Matrix (NIBS, 2007)

Maturity Level	A Data Richness	B Life-cycle Views	C Roles Or Disciplines	G Change Management	D Business process	F Timeliness/ Response	E Delivery Method	H Graphical Information	I Spatial Capability	J Information Accuracy	K Interoperability/ IFC Support
1	Basic Core Data	No Complete Project Phase	No Single Role Fully Supported	No CM Capability	Separate Processes Not Integrated	Most Response Info manually re-collected - Slow	Single Point Access No IA	Primarily Text - No Technical Graphics	Not Spatially Located	No Ground Truth	No Interoperability
2	Expanded Data Set	Planning & Design	Only One Role Supported	Aware of CM	Few Bus Processes Collect Info	Most Response Info manually re-collected	Single Point Access w/ Limited IA	2D Non-Intelligent As Designed	Basic Spatial Location	Initial Ground Truth	Forced Interoperability
3	Enhanced Data Set	Add Construction/ Supply	Two Roles Partially Supported	Aware of CM and Root Cause Analysis	Some Bus Process Collect Info	Data Calls Not In BIM But Most Other Data Is	Network Access w/ Basic IA	NCS 2D Non-Intelligent As Designed	Spatially Located	Limited Ground Truth - Int Spaces	Limited Interoperability
4	Data Plus Some Information	Includes Construction/ Supply	Two Roles Fully Supported	Aware CM, RCA and Feedback	Most Bus Processes Collect Info	Limited Response Info Available In BIM	Network Access w/ Full IA	NCS 2D Intelligent As Designed	Located w/ Limited Info Sharing	Full Ground Truth - Int Spaces	Limited Info Transfers Between COTS
5	Data Plus Expanded Information	Includes Constr / Supply & Fabrication	Partial Plan, Design & Constr Supported	Implementing CM	All Business Process(BP) Collect Info	Most Response Info Available In BIM	Limited Web Enabled Services	NCS 2D Intelligent As-Builts	Spatially located w/Metadata	Limited Ground Truth - Int & Ext	Most Info Transfers Between COTS
6	Data w/Limited Authoritative Information	Add Limited Operations & Warranty	Plan, Design & Construction Supported	Initial CM process implemented	Few BP Collect & Maintain Info	All Response Info Available In BIM	Full Web Enabled Services	NCS 2D Intelligent And Current	Spatially located w/Full Info Share	Full Ground Truth - Int And Ext	Full Info Transfers Between COTS
7	Data w/ Mostly Authoritative Information	Includes Operations & Warranty	Partial Ops & Sustainment Supported	CM process in place and early implementation of root cause analysis	Some BP Collect & Maintain Info	All Response Info From BIM & Timely	Full Web Enabled Services w/IA	3D - Intelligent Graphics	Part of a limited GIS	Limited Comp Areas & Ground Truth	Limited Info Uses IFC's For Interoperability
8	Completely Authoritative Information	Add Financial	Operations & Sustainment Supported	CM and RCA capability implemented and being used	All BP Collect & Maintain Info	Limited Real Time Access From BIM	Web Enabled Services - Secure	3D - Current And Intelligent	Part of a more complete GIS	Full Computed Areas & Ground Truth	Expanded Info Uses IFC's For Interoperability
9	Limited Knowledge Management	Full Facility Life-cycle Collection	All Facility Life-Cycle Roles Supported	Business procs are sustained by CM using RCA and Fdbck loops	Some BP Collect & Maint. In Real Time	Full Real Time Access From BIM	Netcentric SOA Based CAC Access	4D - Add Time	Integrated into a complete GIS	Comp GT w/Limited Metrics	Most Info Uses IFC's For Interoperability
10	Full Knowledge Management	Supports External Efforts	Internal and External Roles Supported	Business processes are routinely sustained by CM, RCA & Fdbck loops	All BP Collect & Maint. In Real Time	Real Time Access w/ Live Feeds	Netcentric SOA Role Based CAC	nD - Time & Cost	Integrated into GIS w/ Full Info Flow	Computed Ground Truth w/Full Metrics	All Info Uses IFC's For Interoperability

Despite the provision of guidance assessing RFQ's and RFP's, it is unclear how all the elements in the documents can be synergised for a comprehensive qualification of potential CSC's for BIM-enabled projects. Furthermore, priority weightings for the RFQ and RFP assessment criteria have not been provided, thus, it is unclear the weight or importance that need to be applied to each criterion. The CIC (2012) framework is generally an implementation advice and guidance document and lacks a comprehensive and computational approach to assessing BIM qualification for the purposes of CSC selection or pre-qualification. Furthermore, there is no apparent academic validation of this framework.

3.3.1.3 Indiana State University BIM Proficiency Matrix

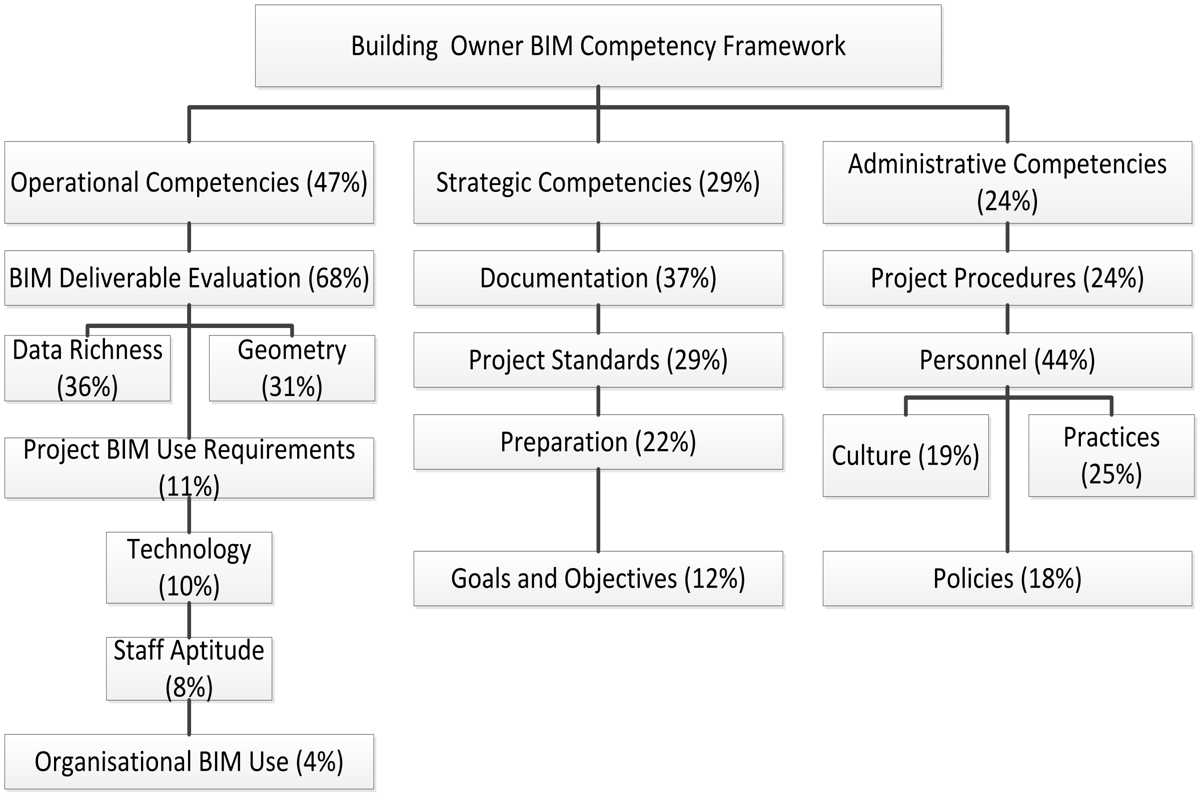
Another tool that has been developed for BIM capability assessments in the USA is the Indiana University BIM proficiency matrix. This tool is capable of assessing BIM capability through evaluation of the experience of potential designers and contractors for new projects (Giel and Issa, 2014). This tool is designed to understand the proficiency of a respondent's skill at working in a BIM environment (IU, 2009). The evaluation is done on the basis of eight critical criteria: physical accuracy of the model, the presence of an Integrated Project Delivery (IPD) methodology, calculation mentality, location awareness, content creation, construction data, as-built modelling and FM data richness. Candidates being assessed are required to provide proof of previous modelling which will be assessed based on these criteria. The tool is based on a static MS Excel spreadsheet (IU, 2009).

This tool, however, lacks academic validation (Succar *et al.,* 2012). The criteria mainly measures product modelling skills and quality, making it inappropriate for full organisational assessment. All of the eight categories of criteria relate mainly to hard technical measures with a focus on only the product aspects of BIM rather than other organisational or people attributes. Thus, process and people issues relating to collaboration are not part of this assessment tool. The method of evaluation further assumes equal weighting to each criterion making it inappropriate in practical evaluation of an organisation's ability to deliver BIM.

3.3.1.4 BIM Owner's Competence Assessment Framework (BIMSCAT)

In response to lack of tools developed specifically for owner organisation, Giel and Issa (2013; 2014; 2015) developed a framework consisting of 66 measures. They adopted three key criteria for the assessment of owner organisation's BIM competence namely strategic, operational and administrative. The tool relies on distinctive measures within the three competence categories (Giel and Issa, 2014). This tool adapts a maturity modelling approach to rating the performance of each criterion. Giel and Issa (2015) adopted six levels of maturity each contributing to 200 points and a maximum score of 1200 points. The criteria relied on was validated through a Delphi study involving BIM experts (n = 21). Giel and Issa (2014) prioritised each criterion to derive a weighted importance based on each measure's mean importance rating. Operational competencies were rated as most relevant followed by strategic competencies and administrative competencies. Operational competency factors represented 47% of the total assessment framework, strategic competency factors made up 29% of the framework, and administrative competency factors made up 24%. The hierarchal structure of criteria and measures adopted in this framework is presented in Figure 3.1.

The main limitation of this framework is the fact that it was designed to evaluate client or owner organisations rather than the CSC (mainly consultants or sub-contractors). Since it was not designed for selection or pre-qualification, there are omissions of important qualification criteria which are more relevant for this phase of projects. Furthermore, the weights allocated to criteria are based on their importance in assessing owner organisations rather than the CSC. The criteria weighted importance is also based on their suitability as assessment criteria rather than their contribution to BIM delivery success.

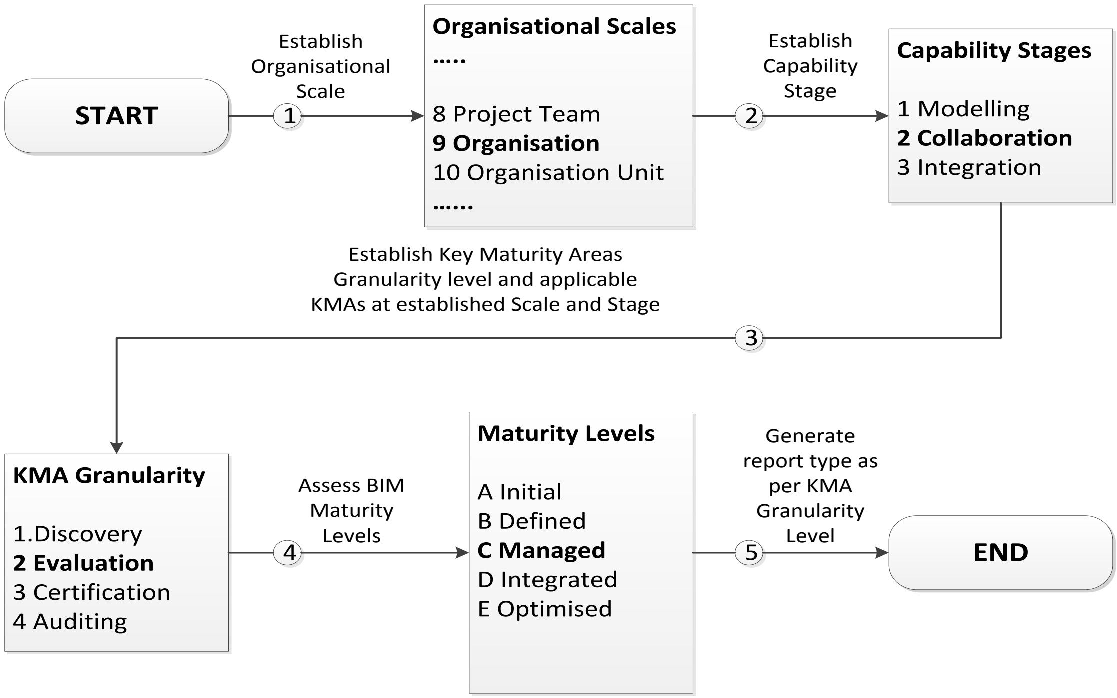


Source: *Giel and Issa (2014) reused with permission from ©ASCE*

Figure 3.1: Framework for Owner Competence Assessment

3.3.1.5 Building Information Modelling Maturity Index (BMMI) and BIM Excellence Services (BIMe)

Following Succar's (2009) framework for BIM research and delivery, a maturity model and an individual competency framework have since been developed and published (Succar, 2010; Succar *et al.,* 2013). The aforementioned relies on five complementary components for comprehensive evaluation of BIM maturity namely: capability stages, maturity levels, competency sets, organisational scales and granularity levels. Figure 3.2 depicts the process flow of different stages of evaluating BIM capability and maturity assessment as specified by Succar, (2010). The key elements of Succar's (2010) framework was applied in the development of the BIM Maturity Index (BIMMI) after a review of over 15 capability maturity models and quality management frameworks (Succar *et al.,* 2012).



Source: *Succar et al. (2012) reused with permission from © Taylor & Francis Group (www.tandfonline.com)*

Figure 3.2: BIM Maturity Determination Flow Chart

Based on the BIMMI, a more detailed BIM Maturity Matrix (BIm3) was subsequently developed (Kam *et al.,* 2014). Assessments are performed on the basis of five levels of maturity (initial, defined, managed, integrated, optimised) and three categories of key maturity areas (technology, process and policy) (Succar *et al.,* 2012). Technology is assessed on the basis of three sub-criteria or dimensions: software, hardware and networks. Process area consists of leadership, infrastructure, human resources, products and services. The policy set area consists of contractual, regulatory and preparatory capabilities. Succar has since developed a commercial tool, BIM Excellence (BIMe) for assessing individual, team, organisational and project BIM capability (BIMe, 2015). BIMe's evaluation system seeks to establish benchmarks for assessing the BIM field and organisation's maturity or competency (Succar *et al.,* 2012; BIMe, 2015).

The main limitation of the BIMMI is that it has been designed to aid assessment of maturity for the purposes of implementation rather than qualification (pre-qualification and selection) for projects. The criteria relied upon, therefore, relate to organisational attributes necessary for internal implementation of BIM. Furthermore the BIMMI relies less on soft organisational capability attributes. Criteria suitable for evaluating pre-qualification and selection documents such as RFPs are not also included.

The BIMe version may have more relevance to pre-qualification and selection. However, BIMe is a commercial tool, hence there is a limited level of detail on the criteria and computational methodologies relied on. Also there are is no reported academic validation of BIMe (Kam *et al.,* 2014).

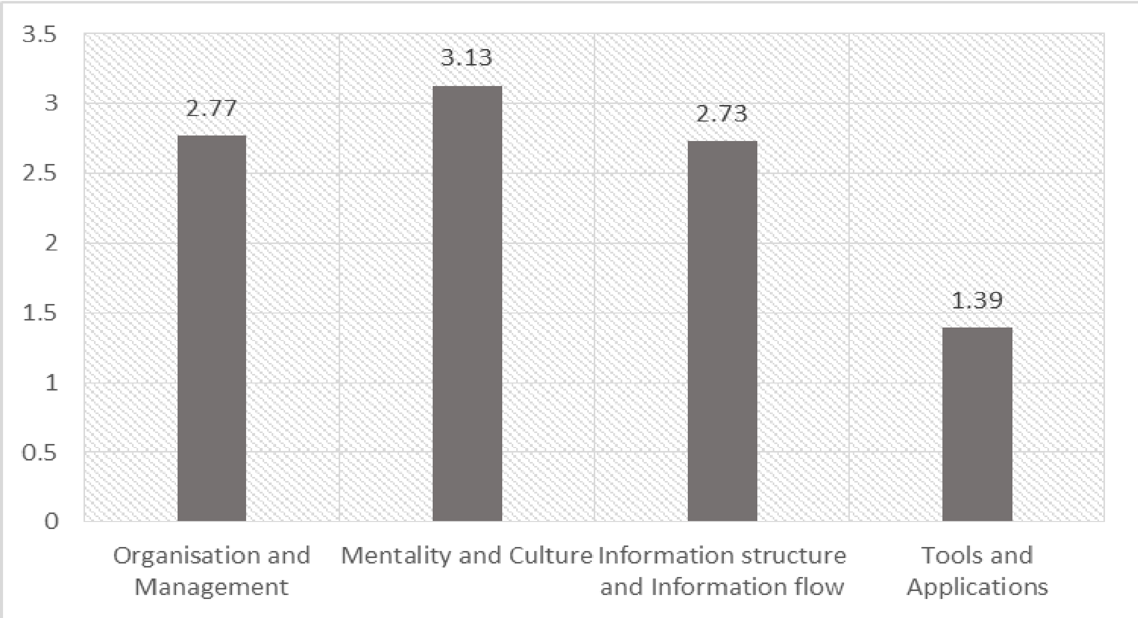
3.3.2 Other BIM Assessment Frameworks and Toolsets

Apart from the capability maturity approach, other assessment tools have evolved for the assessment of BIM capability. These include competence and readiness frameworks which do not follow the capability maturity modelling steps (key process areas and maturity scales). Capability criteria were broadly identified and in some instances, weighted to aid direct scoring and summation. The notable tools are reviewed below.

3.3.2.1 The TNO BIM QuickScan

BIM QuickScan is an evaluation tool created in the Netherlands by the Organisation for Applied Scientific Research (TNO)**.** It is capable of both assessing and benchmarking BIM performance of firms (Sebastian and van Berlo 2010). The key criteria for assessment are organisation and management, mentality and culture, information structure and flow and tools and applications as shown in Figure 3.3 (van Berlo *et al.,* 2012). Criteria priority shows mentality and culture as the most important group (weighted index 3.13) with organisation and management (weighted index 2.77) being the second most important followed by information structure and flow (weighted index 2.73) and lastly tools and applications (weighted index 1.39). Each chapter consists of a series of weighted Key Performance Indicators (KPIs) that can be assessed from responses on a multiple choice questionnaire (Sebastian and van Berlo 2010). The assessment is performed by a group of consultants as this tool is offered for commercial purposes. An abridged self-assessment version, however, exists as an online tool (van

Berlo *et al.,* 2012). BIM Quickscan relies on both quantitative and qualitative assessments criteria and accommodates expert personal judgement (Sebastian and van Berlo, 2010). It covers both hard and soft aspects of BIM and has gone through some validation in assessment of organisations in the Netherlands (van Berlo *et al.,* 2012).



Source: *Serbastian and van Berlo (2010)*

Figure 3.3: BIM Quick Scan Chapters

This BIM QuickScan was primarily developed for usage within the Netherlands and relies on expert evaluations. It is not clear which segment of the CSC this tool was developed for. The BIM QuickScan is also not developed for selection or pre-qualification, thus despite the relevance of the criteria relied on, it is susceptible to omissions that render it unsuitable.

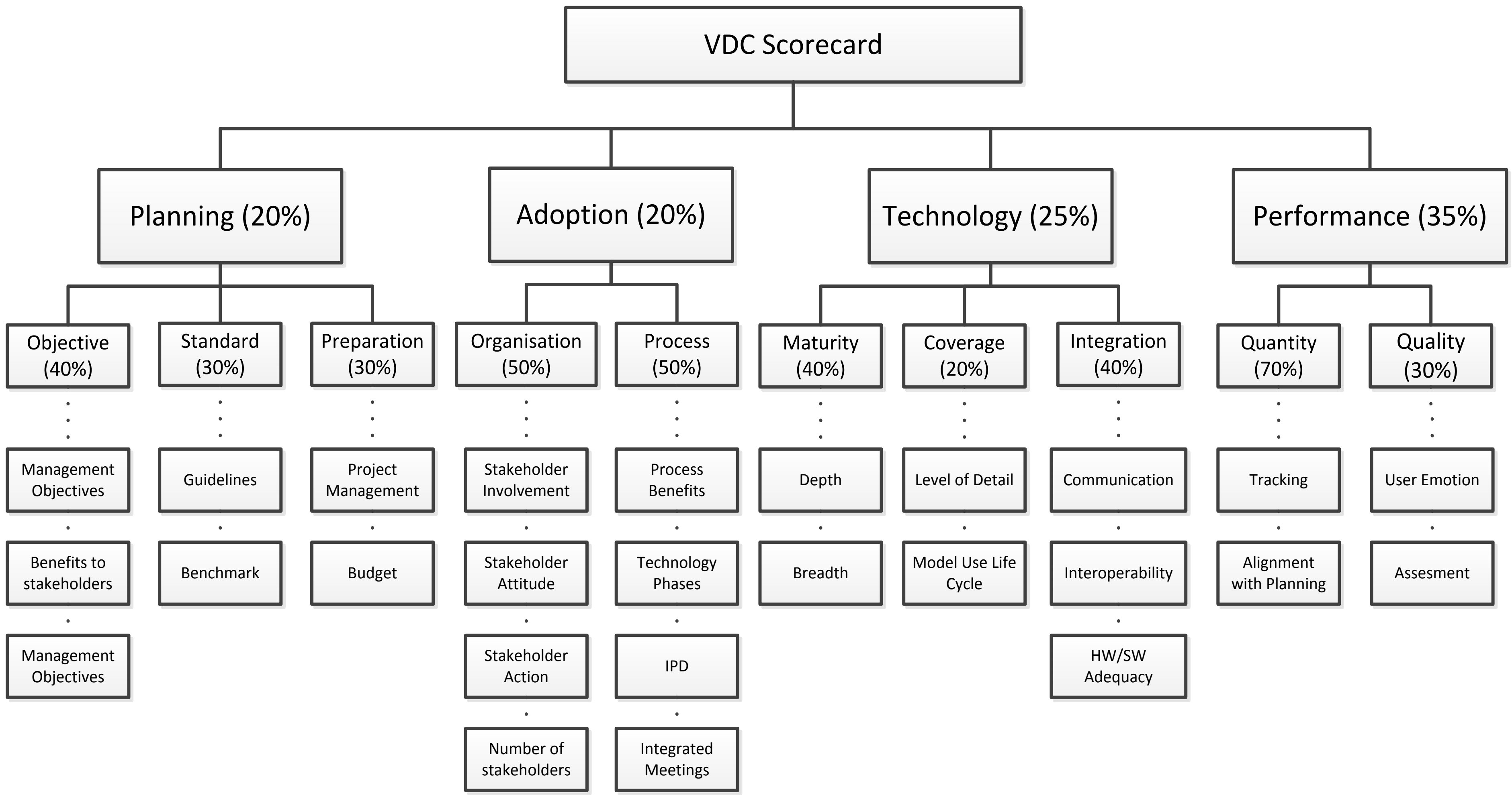
3.3.2.2 CIFE VDC Scorecard and BIMScore

Stanford University Centre for Integrated Facility Engineering (CIFE), in the USA, developed an evaluation tool for assessing the maturity of Virtual Design and Construction (VDC) including BIM) (Kam *et al.,* 2014). This framework can aid construction organisations in assessing the extent of BIM implementation on projects in relation to planning, adoption, technology and performance (Kam *et al*., 2013b). It can be used to assess VDC (including BIM) performances on projects. The VDC Scorecard assesses the maturity of the VDC implementation of a project across four broad areas, ten divisions and with 56 measures (Figure 3.4).

One of the primary objectives was to create a tool that can assist in benchmarking new projects against past, present or even performance of industry standards (CIFE, 2009). A main feature that distinguishes it from tools like CMM or BMMI is the evaluation style. The CIFE VDC Scorecard relies on percentile ranking (Kam *et al.,* 2014). This allows categorisation of performance based on the following grades in ascending order: conventional, typical, advanced, best practice, and innovative (Kam *et al.,* 2013b).

An online tool called BIMScore was subsequently developed based on this framework (BIMScore, 2015). The VDC scorecard has also been validated through a survey of 108 projects from North America, Europe, Asia, and Oceania (Kam *et al.,* 2014). One of the key advantages of the VDC Scorecard (BIMScore) is the ability to track the impact of BIM implementation on project performance (Kam *et al.,* 2014). The performance areas considered include modelling alignment, reduction in RFI expectation, changes and user satisfaction (Kam *et al*., 2013b). As defined by the VDC Scorecard, performance had low Pearson's (Product-moment) correlations coefficients (r) with planning (r = 0.393; $p < 0.05$), adoption (r = 0.361; $p < 0.05$) and technology (r = 0.306; $p < 0.05$) as opposed to the correlations between capability criteria themselves (Kam *et al.,* 2013).

The primary limitation of the VDC scorecard is that it was developed to measure and track the performance of projects rather than evaluate the capability of an individual firm. This tool is therefore most suitable for ongoing projects or for post-project evaluations rather than a tool for prioritising CSC firms for pre-qualification or selection. The hierarchal depiction of the criteria, their weighted importance and measures are presented in Figure 3.4.



Source: *©Kam et al. (2013b) reused with permission*

Figure 3.4: Evaluation Criteria Hierarchy for the VDC Scorecard

3.3.2.3 Building Information Modelling Cloud Score (BIMCS)

Du *et al.* (2014) developed a cloud based benchmarking tool for organisations to compare their performance with peers. The building information modelling cloud score (BIMCS) automatically collects BIM performance data from a wide range of BIM users and compares it with a national database. The performance metrics are collected directly from BIM modelling software, uploaded onto an online platform for statistical analysis. The areas assessed include, model quality, effectiveness, accuracy, usefulness and economy (Du *et al.*, 2014). This tool is neither suitable for organisational assessment or evaluation for the purposes of selection. The attributes measured pertain only to the performance of the BIM model development process rather than capability of an organisation.

3.3.2.4 BIM Readiness Assessment Framework by Haron (2013)

According to Saleh and Alshawi (2005), for an organisation to implement an ICT system, it needs to be in a state of readiness. This requires the assessment of the organisations capability in terms of processes, structure and work environment. Haron (2013) adopted a similar approach to assess the readiness of Malaysian consultants to implement BIM. The aim of this research was to develop a framework of criteria for assessing the readiness of design consultants in BIM implementation. Through multiple case-studies of four design consultancy firms, a four component framework was developed and subsequently validated by 15 industry experts. The key elements of the framework are process, management, technology and people. This model followed a similar structure as previous construction IT readiness frameworks such as BEACON, VERDICT and SPICE (*ibid*).

The key limitation of this framework is that, it was designed to identify implementation weaknesses in design consultancy firms in Malaysia. Thus, it is more of an implementation guidance tool rather than an assessment tool. More so, it cannot be directly applied to BIM qualification of the CSC. Priority weightings to the criteria in relation to their suitability for assessment are not clear nor quantitatively defined. It is not directly applicable to pre-qualification or selection scenarios for CSC organisations, especially, the UK context.

3.3.2.5 Other Industry and BIM Vendor Frameworks

Some software vendors such as VICO Inc. developed their own version of a BIM scorecard for companies to assess their level of BIM integration. The evaluation is developed on the basis of criteria that assess integration in areas of clash detection, scheduling and estimating (VICO Inc. 2016). The tool is designed to aid construction managers to perform BIM performance evaluations. Each key criterion is assessed in terms of its ability to deliver basic functionality and capability, best practice or enterprise integration (VICO Inc., 2016). This is, however, a commercial tool, thus, its academic validity is not clear neither is it directly applicable for pre-qualification or selection.

DeBIM specialist introduced an assessment tool called 'BIM Succespredictor', which comprises of nine criteria: strategy, organisational structure, commitment, people, resources, engineering method, collaboration, BIM scope and results (Hendriks, 2010). These aspects are categorised into corporate aspects and project aspects. The tool seeks to establish the relationship between shortcomings in the implementation process and strategies. The key limitation however, is the reliance on consultants' expert opinion and lack of clarity on the validation process. Moreover, the analysis is not quantifiable, which means that an objective overall comparison or benchmarking between different organisations cannot be easily made (Sebastian and van Berlo, 2010).

According to Sebastian and van Berlo (2010) many other consultants have developed variations of existing toolsets (including Succespredictor by DeBIMspecialist and Succesvoorspeller). More recently, ARUP has developed a tool for assessing BIM performance on projects in the UK (Duncan and Aldwinckle, 2015; ARUP, 2016). This tool is a derivative of the CIC (2012) guidance and adapted to suit ARUP. The key limitation of these tools is the lack of neither academic validation nor clarity on their wider applicability. These frameworks and tools were developed for implementation or project performance assessment rather than BIM qualification of the CSC (pre-qualification and selection).

3.3.3 Empirical Studies on BIM Maturity

In response to the lack of theoretical and empirical justifications for existing BIM capability frameworks and toolsets Chen *et al.,* (2016) investigated factors contributing to BIM maturity (Chen *et al.,* 2012;2014 Dib *et al.*, 2012). Dib *et al.* (2012) identified 27 indices for measuring BIM maturity across planning and management of process and technology, team structure, hardware, process definition, and information management. Through factor analysis, process definition ranked first, while hardware ranked the last in order of importance in the measurement of BIM maturity. Competency profile of staff was not considered very important. Through confirmatory factor analysis, process and information related factors were found to be more important than technology and people related factors (Chen *et al.,* 2014). The key factors accounting for BIM maturity were process definition and management, information management, training, technology and information delivery.

Chen *et al.* (2016) modelled the relationship between BIM maturity factors to guide practitioners in evaluating their BIM implementation using structural equation modelling. Process management and technology management were confirmed as critical to BIM maturity through effective information management. These studies have highlighted important factors that contribute to BIM maturity and therefore can be relied on in assessment of the ability to deliver BIM. However, these studies were not conducted for the pre-qualification or selection phase, thus, susceptible to the omission of criteria more relevant at this phase of projects. BIM maturity factors were looked at in relation to their contribution to BIM maturity rather than their implications on delivery success.

3.4 BIM CAPABILITY CRITERIA USED IN EXISTING FRAMEWORKS

The development of frameworks for BIM capability assessment is dependent on the suitability of the metrics, their accuracy and adaptability in scenarios of application. According to Succar (2010) the validity of an evaluation is dependent on whether or not the criteria relied on meet the objectives of the evaluation. Resultantly, there are noticeable differences in the criteria relied on for most of the existing BIM assessment frameworks and toolsets.

According to Giel and Issa (2013) the criteria adopted as part of toolsets and their frameworks can be categorised as 'process' or 'product' driven. Process-driven criteria refer to attributes used to evaluate organisational processes similar to key process areas used in traditional maturity models (see Succar, 2010; van Berlo *et al.* 2012; CIC, 2013b; Chen *et al.,* 2016). Product-driven criteria often refer to attributes used to evaluate the end product or output (the BIM model) (NIBS; 2007; IU, 2009; NIBS, 2012; Du *et al.,* 2014). Serbastian and van Berlo (2010) provided an alternative classification which they refer to as the 'hard' and 'soft' aspects of BIM evaluation. The hard measures relate to the technical or technological artefacts while soft aspects relate to people and organisational elements of assessment.

Existing tools tend to focus on the hard dimension. Some of the most relevant frameworks for organisational assessment include: the BIMMI (Succar, 2010); CIC implementation guide (CIC; 2012); BIM Quickscan (van Berlo et al., 2012); Malaysian design consultants' readiness framework (Haron, 2013); and the owners' competency framework (Giel and Issa, 2015). Others have categorised the soft criteria as 'people' criteria representing individual competencies in general (Gu and London 2010; Haron, 2013). Chen *et al.* (2016) referred hard criteria as process or technology. In this study a third category is proposed as information management for criteria representing information outputs.

Succar *et al's.* (2012) BIM competency hierarchy provides a broad and generic description of the necessary criteria used in BIM capability evaluations, namely technology, process and policy. The technology category of criteria describes specific abilities related to physical artefacts including software, hardware and data or networks. The process category is used to describe resources, activities, workflows, products, services, leadership and management related capacity for delivering BIM. Finally, Succar *et al.* (2012) describes a policy category encompassing contracts, benchmarks and guidance for attainment of BIM implementation objectives. Dib *et al.* (2012) identified the following as the critical areas for the attainment of BIM maturity: planning and management of process and technology; team structure; hardware; process definition; and information management.

The Pennsylvania State University BIM guide (CIC, 2013b) evaluates organisations maturity in the following key areas: strategy, BIM uses, process, information, infrastructure and personnel. The CIC (2012) BIM implementation document includes a guide for evaluating RFP's and RFQ's with criteria such as price, experience, proposed deliverables, competence and technical capability.

The VDC scorecard consists of the following: BIM planning elements for identification of standards, technologies and resources for projects; BIM technology elements for evaluating model maturity and the success of integration across technologies; BIM adoption elements for organisations and processes as well as motivations, incentives, and business structures; and a performance element for assessing the attainment of project objectives (Kam *et al.,* 2014).

The BIM Quickscan consists of four main categories of criteria (Serbastian and van Berlo, 2010; van Berlo *et al.,* 2012). The first category is management, referring to criteria such as vision and strategy, distribution of roles and tasks, organisation structure, quality assurance, financial resources and partnership on corporate and project level. The second category is organisational culture and focuses on BIM acceptance among staff, group and individual motivation, presence and influence of BIM coordinators, knowledge and skills, knowledge management and training. The third category is data structure and information flow and includes criteria such as use of modelling, open ICT standards, object libraries, internal and external information flow, type of data exchange and type of data in each project phase. The last category is referred to as technology platforms and tools and includes criteria such as use of model server, type and capacity of model server, type of software package, advanced BIM tools, model view definitions and supporting rules.

Haron's (2013) readiness framework also consists of four categories of criteria that indicate an organisations ability to implement BIM. The first is the process element and includes criteria related process change strategy, BIM implementation management and policy. The second readiness element in this framework is management which includes business strategy, management competency and leadership. The third element is technology for assessment of capability in relation to hardware, technical support, and software. The fourth element is people, for the evaluation of roles and responsibilities, skill and attitude as well as training.

Giel and Issa's (2015) framework for evaluating an owner's competence at BIM includes the following criteria: strategic competencies for assessing ability to plan and develop a course of action for BIM execution efforts; administrative competencies for assessing the ability of an owner organisation to manage resources to meet desired internal BIM execution goals; and operational competencies for assessing the ability of an owner organisation to execute BIM at the organisational and project level.

Despite the semantic similarities in the criteria used in these frameworks there remains some difference in the types, description and importance allocated to the various categories of criteria. Apart from the CIC (2012) planning guidance document which recognises standard RFQ (pre-qualification and selection) criteria, all other frameworks and tools do not incorporate criteria specific to pre-qualification and selection. Since most of the frameworks and tools were developed for BIM implementation, they tend to focus on existing process maturity to the detriment of other historical indicators of capability. Furthermore, since these frameworks and toolsets were not developed for selection or pre-qualification, the criteria weightings (importance) cannot be relied on for that purpose. Despite the CIC's (2012) incorporation of some relevant criteria for pre-qualification and selection, no priority weightings are proposed in their guidance document. Therefore, there remains the need for a framework that incorporates criteria and nomenclature specifically developed to aid the qualification of CSC firms for projects.

From a gap analysis of the literature, there remains a constancy of studies based on a hard technological deterministic view of BIM capability, and hence, an over focus on the technical competence and infrastructural capacities (Sackey, 2014; Murphy, 2014). Other studies have also highlighted the importance of the process elements of BIM that drive information sharing and communication (Haron, 2013; Chen *et al.,* 2016). However these studies also remain technology centric. This is unsurprising given that academics and practitioners still view BIM primarily as software or tool rather than a process based innovation for facilitating communications (Murphy, 2014). Thus, there is a growing number of studies that view BIM capability from a soft systems or technology deterministic perspective where the social context within which technology is used is given more focus (Linderoth, 2010; Mahamadu *et al.,* 2014). Resultantly, recent studies have advocated the reliance on readiness attributes related stakeholder cultural and physiological preparedness to use BIM (Adriaanse, 2007; Mahamadu *et al.,* 2014). The studies investigating the factors contributing to BIM diffusion, acceptance and technology readiness have, thus, proliferated (Adriaanse, 2007; Linderoth, 2010; Davies and Harty, 2013; Mahamadu *et al.,* 2014). While these studies have highlighted the importance of attitudinal measures of readiness and human behavioural determinants of BIM competence, it is unclear which specific attributes provide such evidence.

3.5 PRE-QUALIFICATION AND SELECTION WITH EXISTING CAPABILITY FRAMEWORKS

Despite the proliferation of these frameworks and tools, a few of the initiatives have made some progress towards widespread use in practice (Kam *et al.,* 2013a). Despite the successes of these evaluation initiatives, the existing frameworks or tools remain susceptible to omissions and limitations as demonstrated above. Particularly, for the pre-qualification, selection and CSC context where no specific frameworks exists. Table 3.2 and 3.3 shows a review of relevant capability frameworks that have been published with a highlight on the omissions that render them unsuitable for usage in qualifying the CSC firms during selection or pre-qualification.

According to Saleh and Alshawi (2005), IT related capability measurements should be approached on the basis of viewing the technology as an object, process or the organisational environment required to implement it. Most of the models available are, however, focussed on assessing BIM as a product or the technical processes with no tools adequately integrating subjective behavioural attributes that affect capability (van Berlo *et al.,* 2012; Du, *et al.,* 2014). Furthermore, only the CIC (2012) planning guidance acknowledges criteria specific for pre-qualification or selection activities (RFQ and RFP evaluation criteria). However, the CIC (2012) planning guide is only a policy guidance document with no empirical validation or prioritisation of the proposed criteria.

Attitudinal indicators of readiness or maturity have also not been adequately considered by most tools (Haron, 2013). Attitudinal indicators often relate to criteria that measure softer issues including psychometric measures on appropriate organisational culture and technology readiness (Sebastian and van Berlo, 2010). Current approaches, therefore, tend to focus on hard organisational capabilities for assessing BIM capability (Haron, 2013; Giel and Issa, 2014). Another major methodological challenge has been identified as a lack of scientific underpinning in the methods used for developing these frameworks as well as methods for analysis and validation (Kam *et al.,* 2014; Giel and Issa, 2015; Chen *et al.,* 2016). This is attributed to the fact that some have been developed by industry bodies and organisations rather than academia.

From the review of BIM capability frameworks and toolsets, the summary of the critical limitation is presented below:

- Lack of academic validation and theoretical underpinning;
- Criteria prioritisation not based on empirically established relationships between capability attributes and various elements of BIM delivery success;

Table 3.2: A Review of Relevant BIM Capability Frameworks and Toolsets (Part 1)

Framework or Toolset	**NBIMS Capability Maturity Model (CMM) (NIBS, 2007)**	**BIM QuickScan (van Berlo *et al.*, 2012)**	**VDC Score Card (Kam *et al.*, 2013b and Kam *et al.*, 2014)**	**Readiness Framework (Haron, 2013)**
Developed by	NBIMS - The National BIM Standard (USA)	TNO - The Netherlands Organisation for Applied Scientific Research	CIFE - Centre for Integrated Facility Engineering- Stanford University (USA)	PhD research by Haron (2013) University of Salford, UK
General description	Capability maturity model for assessing firm's process maturity in delivering BIM	Evaluates BIM performance level of organisations providing BIM services	Evaluates project BIM implementation and performance	Readiness assessment framework for Malaysian design consultants
Focus of evaluation	Product (BIM Model)	Process and People	Product, Process and People	Process and People
Evaluation methodology	Self-evaluation	Consultant led evaluation or online self-assessment (abridged version)	Mainly consultant led, web tool could be used for self -evaluations	Generic framework (academic)
Main criteria	Data richness; Life-cycle views; Roles or disciplines; Change management ; Business process Timeliness; Response; Delivery method; Graphical Information; Spatial capability; Information accuracy Interoperability and IFC Support.	Organisation and management; Mentality and culture ; Information structure and flow; and Tools and applications (*KPI's:* Strategic, organisation, resources, partners, mentality, culture, education, information flow, open standards and tools)	Planning; Adoption; Technology; and Performance. (*Dimensions of Measurement:* Objective, Standard, Preparation, Organisation, Process, Coverage, Maturity; Integration, Quality and Quantity)	Process; Management; Technology; and People. (Sub elements: strategy, policy, management competency and leadership, hardware, technical support, software, roles and responsibilities, skill and attitude and training)
Rating or maturity levels	10 Maturity levels aggregated based on weighted criteria	10 Weighted KPI's in 4 main sections	10 Weighted criteria in 4 main sections	N/A
Final score/ presentation style	Minimum BIM, certified, silver, gold and platinum	Aggregated percentage score	Conventional practice, typical practice, advanced practice, best practice, and innovative practice	N/A
Final score evaluation method	Summation of weighted scores	Summation of weighted scores	Summation of weighted KPIs in 5 percentile ranges of increasing innovation in practice	N/A
Developed for UK CSC?	No	No	No	No
Criteria include people and attitude related attributes?	No	Yes	Yes	Somewhat
Designed for selection /pre-qualification?	No	Requires Adaptation	No	No

Table 3.3: A Review of Relevant BIM Capability Frameworks and Toolsets (Part 2)

Framework or Toolset	**BIMMI (Succar, 2009; Succar, 2010)**	**CIC (2012)**	**UI BIM Proficiency Matrix (UI, 2009)**	**Owner competence framework (Giel and Issa, 2014; 2015)**
Developed by	Academic publications and conceptual frameworks by Bilal Succar	CIC - Computer Integrated Construction Research Program - Pennsylvania State University USA	UI - University of Indiana, USA	PHD Research - Rinker School of Construction Management, University of Florida (USA)
General description	Process maturity assessment	BIM Implementation guidance document	Evaluates designers and contractors' ability to deliver BIM services	Evaluates the BIM competency level of building owners/clients
Focus of evaluation	Process and Product	Process, Product and People	Product , Process	People, Process, Product (organisation)
Evaluation methodology	Maturity model	Self-evaluation by internal experts with maturity matrix element	Maturity matrix evaluation based spreadsheets	Assessment framework (academic)
Main criteria	Technology; Process; and Policy (*Elements:* Software, Hardware, Data and Networks, Resources, Activities and Workflow, Product and Services, Leadership and Management, Benchmarks and Controls, contracts and Agreements, Guidance and Support)	Strategy; BIM Uses; Process; Information; Infrastructure Personnel. (Additional guidance on Request for proposal [RFP] and Request for qualification [RFQ]: Price, execution plan, technical capacity and experience)	Integrated Project Delivery (IPD) methodology; Calculation mentality Location awareness; Content creation; Construction data; As-built modelling and FM data richness	*Operational Competence; Strategic Competence; and Administrative Competence.* (*Sub elements:* BIM Deliverable, Project BIM use, Technology, Staff Aptitude, Organisational BIM use, Documentation, Project Standards, Preparation, Goals and Objectives, Project Procedures, Personnel, Policies)
Rating or maturity levels	4 Competency levels; 3 Capability stages; and 5 Maturity levels	6 Maturity levels	5 Proficiency levels	6 Maturity levels
Final score/ presentation style	Summated allocated of points	Summated allocated of points	Working towards BIM, Certified BIM, Silver, Gold, Ideal	Non-existent, Initialized, Managed, Defined, Quantitatively managed, Optimizing
Final score evaluation method	Summation of allocated points	Summation of allocated points	Simple summation of equally weighted allocated points	Summation of weighted scores on each maturity level
Developed for UK CSC?	No	No	No	No
Criteria include people and attitude related attributes?	Somewhat	Yes	No	Yes
Designed for selection /pre-qualification?	No	Can be adopted	No	No

- Framework or definitions are not intuitive to practitioners, thus, remain obsolete to the pre-qualification and selection context;
- Lack of comprehensive consideration of product, process, people notwithstanding hard and soft behavioural and attitudinal aspects in measurement of capability;
- Commercial interest and involvement in tool development; and
- Challenges in complementarily use of the different frameworks and tools due to variations in the type of criteria focus and weighting allocated to each criteria

3.6 CHAPTER SUMMARY

A review of frameworks and toolsets on BIM capability assessment has been presented together with the suitability of theses frameworks or tools for qualifying CSC for projects. The adaptation of criteria as qualification criteria during pre-qualification and selection is also presented. From the review it is concluded that, despite the assumption that BIM technologies and process requirements are generic, the applicability of criteria and methodologies require contextual validation albeit for pre-qualification and selection. In the next chapter, the implications of BIM qualification criteria on delivery success are explored from a review of tendering, pre-qualification and selection literature.

CHAPTER 4: BIM QUALIFICATION AND DELIVERY SUCCESS

4.1 INTRODUCTION

The attainment of success in construction is highly dependent on the selection of qualified organisations to execute projects. With the advent of SCM and other new forms of procurement, the number of CSC organisations that participate in projects has increased tremendously. Success, therefore, invariably depends on the qualification of these CSC organisations. Resultantly, a number of studies have investigated the impact of qualification criteria on project delivery success. Recently, the qualification of organisations based on their BIM capability is becoming a prerequisite in construction. There is, therefore, a need to study the relationship between BIM qualification criteria and delivery success. This chapter presents a review of studies in construction success in order to identify key success areas related to BIM and the CSC. Furthermore, a review of empirical studies on the relationship between qualification criteria and delivery success is presented.

4.2 THE CONCEPT OF SUCCESS AND CONSTRUCTION PROJECTS

There are a growing number of studies on project success within construction management literature. Some studies have examined how to measure success while others have explored the factors that influence success. A number of definitions have, thus, been proffered to explain the concept of success in construction management. According to Chan (1996), success must be considered mainly in relation to the delivery of technical performance specifications. Others have provided a more expansive view of project success, describing it as the degree to which project objectives are met (Chan *et al.,* 2002). Chan and Chan (2004), on the other hand, described success in construction as the development of measures to benchmark the desirability of project outcomes. Based on these definitions a number of indicators have been proposed as the key measures of success in the delivery of construction projects.

4.2.1 Key Construction Success Indicators

Based on the definitions of success (*ibid*), there remains a level of vagueness and a lack of a unified view on the appropriate indicators of success (Ahadzie *et al.*, 2008). There is, however, a wide acceptance of the attainment of quality, schedule (time) and budget (cost) as the most critical indicators of success (Chan *et al.,* 2002). This has traditionally been referred to as the 'iron triangle' of project performance (Ahadzie, 2007). More recently, it has been advocated that, other project objectives be considered in addition to the 'iron triangle' (Toor and Ogunlana, 2010). According to Collins and Baccarini (2004), the traditional view of success refers more to project management success rather than success in the entire delivery process. This assertion is supported by Shenhar *et al.* (1997) who referred to project management success as an internal measure of project efficiency while project success is concerned with a project's external effectiveness. A number of other success measures have, thus, been proposed over the last few decades. They generally relate to the need for delivery of value, customer satisfaction, safety and sustainability. Some of the key indicators of success from construction management literature is presented in Table 4.1.

Table 4.1: Summary of Widely Used Success Indicators in Construction

Success Criteria	References
Quality	Kumaraswamy and Thorp (1996); Songer and Molenaar (1997); Chan *et al.* (2002); Takim and Akintoye (2002); Doloi (2009a) Doloi *et al.* (2011); Al-Zahrani (2013).
Schedule (Time)	Kumaraswamy and Thorp (1996); Songer and Molenaar (1997); Chan *et al.* (2002); Takim and Akintoye (2002); Doloi (2009a) Doloi *et al.* (2011); Al-Zahrani (2013).
Budget (Cost)	Kumaraswamy and Thorp (1996); Songer and Molenaar (1997); Chan *et al.* (2002); Takim and Akintoye (2002); Doloi (2009a) Doloi *et al.* (2011); Al-Zahrani (2013).
Collaboration	Kumaraswamy and Matthews (2000); Pala *et al.* (2014)
Disputes and Litigation	Kerzner (1998); Chan *et al.* (2002)
Health and Safety	Kumaraswamy and Thorp (1996); Chan *et al.* (2002); Ahadzie *et al.* (2008)
Environment	Takim and Akintoye (2002); Chan *et al.* (2002); Ahadzie *et al.* (2008)
Client Satisfaction	Songer and Molenaar (1997); Takim and Akintoye (2002); Chan *et al.* (2002)

According to Toor and Ogunlana (2010) success must be looked at in relation to the context within which it is being assessed. Thus, the adoption of success indicators must be consistent with the primary goals for evaluating success. Resultantly, when looking at BIM in a CSC context, success indicators need to be tailored specifically towards the primary objectives of using BIM to achieve CSC objectives.

4.2.2 The Concept of Critical Success Factors

One of the important concepts in construction project success is the identification of critical factors that contribute to the attainment of success. Such factors are referred to as Critical Success Factors (CSF). A CSF is described as a manageable critical factor responsible for the attainment of a desirable performance (Tsai *et al.,* 2014). This concept was introduced first by Rocart (1979) and has gradually become part of mainstream management research including construction and BIM studies. According to Belassi and Tukel (1996), the determination of success or failure is dependent on knowledge of the interactions between CSFs and success indicators. Several studies have investigated the role of CSFs in construction project performance (Al-Zahrani, 2013). However, these studies tend to be generic making them suited for performance management rather than for qualification of organisations. A few studies have, however, highlighted the importance of CSFs in BIM implementation (Shang and Shen, 2014; Mom *et al.*, 2014; Tsai *et al.,* 2014), as well as qualification of organisations for projects (Al-Zahrani, 2013; Al-Zahrani and Emsley, 2013; Doloi, 2009a)

Mom *et al.* (2014) and Tsai *et al.* (2014) identified the following as CSFs for BIM implementation: organisational strategy; leadership; readiness; capabilities and resources; BIM application; BIM tools; BIM Business model; and BIM processes. Based on Kendall's correlation analysis, the causal relationship between 58 CSFs in the above categories were modelled from a survey of BIM users in Taiwan (Mom *et al.*, 2014; Tsai *et al.,* 2014). The findings revealed that support from top management and functionality of BIM tools are the most critical contributors to delivery of business value through BIM. Shang and Shen (2014) reviewed CSFs for BIM implementation and highlighted the importance of legal issues, technical, organisational and process collaboration. While these studies highlight the applicability of CSFs in BIM research, the success indicators examined were not expansive enough. Mom *et al.* (2014) and Tsai *et al.* (2014) only identified the impact of CSFs on business value rather than other indicators of success in general (such as the ones reviewed in *Section 4.2.1*). Shang and Shen (2014) also acknowledged the importance of collaboration as a success indicator in BIM delivery.

In relation to pre-qualification and selection, Al-Zahrani (2013) recommends the application of the CSF concept in identifying relevant qualification criteria. None of the existing CSF studies in BIM, however, drew explicit links between BIM CSFs and the qualification of CSC for BIM-enabled projects. A review of the studies on the relationships between success and qualification criteria is presented in the next section (*Section 4.4).*

4.3 SUCCESS AND THE QUALIFICATION OF ORGANISATIONS FOR PROJECTS

The qualification of organisations on to projects is regarded as one of the most important functions of a project. It is at this stage that the most suitable candidate is selected based upon a review of their ability to deliver (Russell *et al*., 1992). Ultimately, the selected candidates must be able to contribute their individual expertise to overall project success. This phase is characterised by evaluations of an organisations competencies and invariably a prediction of the likelihood of the selected organisations to succeed. The steps involved in the qualification process as well as the implications of the qualification criteria on delivery success are presented below.

4.3.1 The Pre-qualification and selection Process

Lowest cost continues to be the most important consideration for qualification though increasingly becoming limited as a sole attribute in predicting organisations ability to deliver on projects (Kumaraswamy and Matthews, 2000; Hosny *et al.,* 2013). In order to minimise the risk of selecting incapable organisations, the process for evaluating alternative candidates must be methodical, thorough and complete in relation to each candidate's ability to succeed (Holt *et al.,* 1994; Plebankiewicz, 2012). Both clients and main contractors, however, continue to be faced with the challenge of assessing prospective candidates to be part of their CSC due to the need for the consideration of their capability in multiple areas (Hartmann *et al.,* 2009). With the emergence of BIM, the ability to deliver through BIM has become a key requirement as outlined in *Section 2.3*.

The qualification phase is characterised by two main activities, pre-qualification and selection. The selection process involves the direct selection of a suitable candidate for the contract award upon presentation of evidence of their competence (Kumaraswamy and Matthews, 2000; Cheung *et al.*, 2002). Pre-qualification provides the opportunity to shortlist a smaller list of organisations to be invited to tender on a regular basis (Plebankiewicz, 2012). This is particularly important as many principal suppliers (usually main or prime contractors or construction management contractor) rely on the same CSC for several projects (Manu, 2014). It, therefore, allows a preliminary assessment of acceptable capability to enable preliminary acceptance on the supply chain of a principal supplier (Pryke, 2009).

Several studies have explored the criteria or methodologies required for effective qualification of construction (CSC) firms for construction projects (Russell *et al*. 1992; Holt *et al*., 1995; Fong and Choi, 2000; Nieto-Morote and Rus-Vila, 2012; Plebankiewicz, 2012). Most of these studies were, however, specific to contractors and sub-contractors, with very few focussing on other segments of the CSC (notably consultants, designers, material suppliers).

Fong and Choi (2000) investigated the interrelationships between nine selection criteria based on expert opinion namely: tender price, financial capability, past performance, past experience, resources, current workload, past relationship and safety management. The Analytical Network Process (ANP), was used to rank a group of contractors based on the most suitable to execute projects. Despite the ability of ANP to model relationships between these criteria, this study did not explicitly examine any relationships between the qualification criteria and success indicators.

Russell *et al*. (1992) investigated the impacts of 20 factors related to contractor pre-qualification and selection decisions. Their study was based on perceptions of 150 public and private owners, and 42 construction managers. Through non-parametric (spearman) rank correlation analysis, financial stability, experience and past performance of the contractors were identified as the most critical qualification criteria for selection of contractors to deliver projects.

In order to address the non-linear nature of contractor pre-qualification and selection problems some studies have incorporated computational methods to reduce bias. Nguyen (1985) incorporated fuzzy set theory in the development of a contractor evaluation model. This paved the way for the development of a new generation of models, including Nieto-Morote and 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 on Fuzzy-AHP. The Fuzzy Set approach allows mathematical modelling of uncertainty and vagueness of the sometimes subjective judgements associated with evaluation of alternatives.

While the studies identified above have highlighted the relevant qualification criteria and computational methods for selecting suitable candidates for construction projects, they failed to investigate the relationship between such criteria and project success. However, according to Holt (1998) and Doloi (2009a), the main premise on which an organisation should be selected for project must be their likelihood to succeed or meet the project objectives. None of the studies have also investigated BIM qualification criteria nor focussed on the ability to deliver BIM successfully in the CSC context (Mahamadu *et al.,* 2015).

4.3.2 Predicting Success during the Qualification Process

The criteria for qualifying organisations during pre-qualification or selection are becoming more diverse but still remain pre-emptive (Doloi, 2009b). According to Doloi (2009a), the study of qualification attributes as a proxy for predicting likely success, provides many benefits to decision making at the qualification or selection stage. This increases the chances of selecting firms with the most likelihood of success, thereby reducing the risk of failure in the first instance (Doloi, 2009a). There is evidence from several studies which suggest that the risk of failure increases when the wrong organisations are selected to deliver a project (Holt *et al.,* 1994). There will, therefore, be a more front-end approach to risk management hence an earlier opportunity to mitigate the risk of failure.

Consequently, a few studies have recognised this notion and attempted to explain the inter-dependencies and relationships between qualification criteria and success indicators in construction.

4.3.3 Empirical Studies on Impact of Qualification Criteria on Delivery Success

One particular study which sought to draw a direct relationship between qualification criteria and success was Hatush and Skitmore's (1997) study of construction firms in Australia. In this study, the relationship between 20 contractor selection criteria and project success (time, cost and quality) was investigated. This was based on the perceptions of eight industry experts in a Delphi study. Past failures were found to be the only criterion that affects all the categories of project success. The criteria found as commonly important for all three success factors were financial status, financial stability, credit rating, experience, ability, management personnel and management knowledge (Doloi, 2009a).

Holt *et al*. (1995) recommended the need for pre-qualification practice after a review of existing methods for contractor selection. This study highlighted the need to assess contraction organisations in relation to their delivery of quality and within time and cost. In another study, the effect of partnering principles in sub-contractor selection was investigated (Kumaraswamy and Matthews, 2000). It was established that partnering principles may contribute up to 10% of reduction in tender prices in addition to better performance in relation to cost, time and quality. This study, however, looked at only sub-contractor perspectives. Furthermore, the focus of the study was on partnering principals rather than general qualification criteria. Nonetheless, the findings highlighted the existence of relationships between certain qualification criteria and project success.

Palaneeswaran and Kumaraswamy (2000) developed a knowledge mining model for tackling contractor selection in design-build procurement. The pre-qualification criteria used in this study were not, however, found to be useful in predicting any quantifiable project success indicators. In a similar study, Doloi (2009a) used multiple regression analysis to investigate the impact of 43 qualification 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 performance. This was based on an assessment of contractor's performance in relation to time, cost and quality of projects in Australia. Through a preliminary factor analysis, *soundness of business and workforce* explained the largest proportion of variance in project success (17.80%) with *planning and control* emerging as the second most important factor and explaining 12.70% of variance. The qualification criteria with the highest regression coefficients (β) for delivery success were technical expertise of contractors (β = 0.407) for time success, appropriateness of the work method statement (β= 0.353) for project quality and past track record of a contractor (β = 0.457) for cost success. In a similar study, Doloi *et al.* (2011) modelled the impact of 29 technical attributes on project success. The technical attributes considered are often used as qualification criteria and included soundness of business and workforce, planning and control, quality performance and past performance. Based on a structural equation model, planning and controlling expertise emerged as the most critical in achieving success on projects.

Doloi (2009b) investigated the links between relational partnership attributes and partnership success on projects. The relational attributes investigated have been considered as qualification criteria in previous studies and included communication, trust and confidence and joint risk management. Based on a questionnaire survey, a structural equation model was used to explain the relationships between these attributes and success (Doloi, 2009a; 2009b). Communication was identified as the single most influential factor impacting relational partnering success. Despite not being directly related to qualification and selection, this study provides some insight into how these relational attributes could be incorporated as qualification criteria for projects on which partnership success is a critical. It further highlights the methodological possibilities of assessing relationships between qualification criteria and success indicators.

Arslan *et al.* (2008) and Arslan (2012) proposed that qualification criteria must be categorised based on their contribution to the attainment of quality, cost, time and overall final acceptance. This was used in the development of web-based Decision Support System (DSS) for evaluation of subcontractors (USA) and contractors (Turkey) respectively. Despite the acknowledgment of project success indicators in the evaluation of construction organisations, this study did not directly investigate the impact of individual criteria on the various success indicators. It did, however, highlight the importance of success prediction through DSS during the pre-qualification or selection phase of projects.

Al-Zahrani and Emsley (2013) studied the impact of construction qualification related attributes on project success from a post construction perspective. Through factor analysis, nine underlying determinants of success were identified as: safety and quality; past performance; environment; management and technical aspects; resource; organisation; experience; size or type of pervious projects; and finance. The impact of these criteria on various success indicators were then modelled through logistic regression analysis (Al-Zahrani and Emsley, 2013). The success indicators modelled were delivery on schedule, budget, quality, an overall success. *Health, safety and quality* related criteria explained 19.4% of the total variance in the attainment of success while *past performance* emerged as second most important factor accounting for 9.2% of variation in the attainment of success. The qualification criteria within the highest logistic regression coefficients was Adequacy of labour (β = 1.284) for schedule success and (β = 1.224) for budget success, *size of past project completed* (β = 0.893) for delivery of quality and Quality policy (β = 1.103) for overall contractor impact. Based on the same data, Al-Zahrani (2013) also modelled the impact of these attributes through Neural Network (NN) models resulting in similar results. Both studies highlighted significant relationships between qualification criteria and project success.

Despite the emergence of these studies, most tend to focus on general qualification rather than specific scenarios such as BIM and CSC context. Understandably, almost all the studies predate the emergence of BIM, thus, criteria considered in these studies do not relate to BIM capability or BIM delivery success, more so in the UK CSC context. Smits *et al.* (2016) surveyed 890 organisations in the Netherlands to identify the influence of CIC (2012) maturity elements on project performance. The maturity elements investigated in this study were strategy, BIM uses, process, information, infrastructure and personnel. Surprisingly, few statistically reliable associations were found between BIM maturity and project success KPIs (time and cost) with inconclusive findings on effect on delivery of project quality. Only strategic level maturity was found to marginally predict time, cost and quality performance of projects albeit small statistical effect sizes. Smits *et al.* (2016), thus, cautioned against over optimism in the expectations that BIM will improve project performance. Despite the relevance of this study, the performance factors investigated related to project success rather than success in the delivery of BIM itself.

4.3.4 Success Indicators Used in Existing Empirical Studies

Most previous studies investigating the impact of qualification attributes on success have often relied on the 'iron triangle' of construction performance. Doloi, (2009b) measured the impact of qualification criteria on time, cost and quality. Doloi *et al.* (2011) measured success in relation to budget, cost savings, quality and time. The success indicators considered by Al-Zahrani and Emsley (2013) were schedule, budget, quality, and overall success of a project. Conversely, Arslan *et al.* (2008) and Arslan (2012) proposed that qualification criteria must be categorised based on the attainment of quality, cost, time and overall final acceptance or adequacy. According to Arslan *et al.* (2008) this categorisation was based on the fact that subcontractor organisations often underperformed in these key areas, necessitating the need for evaluation of attributes that relate to their attainment. It is clear that studies investigating the relationship between qualification criteria and success have often relied on the 'iron triangle' view of success. This is consistent with the review of literature in *Section 4.3*. Based on Toor and Ogunlana's (2010) assertions, success must be looked at in relation to the context within which it is being assessed. Thus, the application of success indicator concepts such as the 'iron triangle' is reviewed in the BIM and CSC context below.

4.3.5 Success in the BIM and Construction Supply Chain Context

As a result of the novelty of BIM, there is a scarcity of studies that examine BIM delivery success. A review of BIM benefits and performance assessment literature, however, provides useful pointers to appropriate indicators of success. More so, it highlights the applicability of the traditional view of success to BIM delivery. For instance, Mom *et al.* (2011) acknowledge the importance of quality, time and cost in the delivery of value through BIM. Kam *et al.* (2014) further outlined the role of BIM capability on project success through a study of the relationship between implementation maturity and project performance. The performance factors considered bare similarity to traditional construction success indicators as reviewed above. They included: communication, cost, schedule, facility management, safety, satisfaction and project management (Kam *et al.,* 2013b; 2014). Despite the similarity of these performance indicators to traditional success indicators (*the iron triangle*), they did not focus on BIM delivery success itself but rather BIM's impact on project delivery success (Mom *et al.,* 2011; 2014; Kam *et al.,* 2014).These studies, however, acknowledge the importance of the traditional view of construction project success to BIM delivery success. Smits *et al.* (2016) surveyed 890 organisations in the Netherlands to identify the influence of CIC (2012) maturity elements on project performance relying on the *iron triangle* metrics (quality, cost and time). Despite the relevance of this study, the performance factors investigated related to project success rather than success in the delivery of BIM itself.

According to Atkins (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 should be based on data accuracy, timeliness, control and auditability (Atkins, 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 construction. Du *et al.* (2014) developed a framework for benchmarking BIM modelling performance. This framework similarly relied on measures consistent with the 'iron triangle' view of success. The measures used were BIM model quality (including effectiveness, accuracy and usefulness), modelling productivity (time) and economy (cost). Thus, as stated in Al-Zahrani (2013), the iron triangle remains the most universally applicable success indicator in the construction context. They can, therefore, be applied to the assessment of BIM delivery success as demonstrated in Atkins (1995) and Du *et al.* (2014) and outlined below:

- **Quality of BIM Delivery:** Quality is generally regarded as the totality of features required of a product or services to meet its primary function (Songer and Molenaar, 1997). While its assessment could be subjective, it is generally accepted as delivering products or services to specification (Songer *et al.,* 1996). BIM delivery quality can therefore be said to have been achieved when a model meets specification. This includes accuracy, usefulness of data as well as general fitness of purpose (Du *et al.,* 2014; Tsai *et al.,* 2014). Since poor information quality has been attributed to poor performance of the CSC, it is expected that the use of BIM will enhance information quality and invariably CSC performance on projects (Vrijhoef, 2011).
- **BIM Delivery on Schedule (time):** Time overrun is one of the most pervasive problems in construction (Hatush and Skitmore, 1997). Similarly, when BIM outputs are not delivered on time it tends to affect the entire project's delivery times (Du *et al.,* 2014). The ability to deliver goods including information on schedule is regarded as one of the critical indicators of success in SCM (Pryke, 2009). Therefore, one of the CSC's expectations of BIM is the ability to deliver project information on time. Du *et al.* (2014) refers to this as modelling productivity and considers it as one of the key performance areas of BIM delivery. Timeliness of information delivery improves CSC communication tremendously and is regarded as key to achieving the strategic objectives of CSC through BIM (Vrijhoef, 2011).
- **BIM Delivery within Budget (cost):** One of the most important objectives of SCM is delivery of goods and services within cost (Khalfan *et al.,* 2015). Invariably, where BIM is used, it is expected that this objective is still met. According to Du *et al.* (2015) an economical approach to BIM data delivery is one of the key performance areas of BIM performance benchmarking.

Hence, just as this has generally been considered in construction success literature, the delivery of BIM within budget is an important indicator of success.

In relation to the other strategic objectives of the CSC, a review of the performance expectations of BIM provides some basis for classifying success indicators. In Pryke's (2009) view, the main objective of SCM is to deliver the right products, in the right quantities, at the right place, at the right time and at minimal cost. To achieve this, the SCM has four roles in the CSC: 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). These can be effectively achieved through the use of IT systems to enable collaboration, coordination and integration (Pryke, 2009).

According to BIS (2012a; 2013b), BIM delivery success in the UK CSC will depend on the ability of principal suppliers to achieve the following: coordination of design, delivery and site operations; change, focus on reducing the opportunity costs; coordination of related trades in a disaggregated CSC's; and early contractor and sub-contractor involvement. Similarly, 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 enhances collaboration in CSC (Papadonikolaki *et al.* 2015a). Furthermore, BIM is also expected to improve value driven long-term relationships for improved performance (Vrijhoef, 2011). BIM use in the CSC is widely expected to contribute to this through better collaboration. There is also, wider expectation that improved collaboration and coordination will foster a more vertically integrated CSC with BIM serving as the integrator (Vrijhoef, 2011; Khalfan *et al.,* 2015; Papadonikolaki *et al.,* 2015a). In addition to quality, timeliness and economic delivery of information through BIM, delivery success in the CSC will also be dependent on the attainment of the strategic objectives of SCM as outlined above.

From the review of UK Government policy (BIS, 2011; 2013a; 2013b) and a review of academic studies (Pryke, 2009; Lönngren *et al*., 2010; Vrijhoef, 2011; Papadonikolaki *et al.,* 2015a), 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 can be facilitated by BIM (Vrijhoef, 2011). Data communication and ability to exchange sensitive information in a more secure manner is very important for collaborative decision making in the CSC (Papadonikolaki *et al.*, 2015a).
- **Coordination:** CSC is functionally characterised by fragmentation that prevents effective convergence of materials, goods and services on site efficiently (Manu, 2014). Cross functional coordination is vital to achieving this through BIM-based communications and the planning of operations through visualisation and virtual prototyping of sites (Vrijhoef, 2011). For instance, when BIM is used with tracking technologies in the CSC it could facilitate lean SCM including just-in-time deliveries (Costin *et al.,* 2014; Khalfan *et al.,* 2015).
- **Integration:** The CSC is also characterised by structural fragmentation. BIM, however enables technologically seamless organisational structures (Papadonikolaki *et al.*, 2015a). Thus, centralised communication leaves the disparate organisations to work better as a single unit (Vrijhoef, 2011).

A summary of the relevant BIM delivery success indicators for the CSC context is provided in Table 4.2.

4.3.6 Predicting BIM Delivery Success through Qualification

Based on CSF principles Mom *et al.* (2014) identified 80 success factors for BIM implementation. Several of the CSFs identified related to BIM capability including organisational readiness, capabilities and resources, BIM applications, BIM tools, BIM processes within organisations (Mom *et al.,* 2014).

Table 4.2: A Summary of Key Indicators of BIM Delivery Success in Supply Chain Context

BIM Success in CSC	Description	Sources
Quality	Overall conformance to technical requirements [i.e. client or project and specifications (including accuracy, usability of data or BIM models)].	Salmeron (2010); Mom *et al.* (2011); Du *et al*. (2014); Mom *et al.* (2014); Tsai *et al.* (2014).
Schedule (timeliness)	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)	Attainment of BIM deliverables within budget.	
Collaboration through BIM	Trust-based relationship and commitment for the attainment of common business objectives through transparent and effective communication.	Pryke (2009); Lönngren *et al*. (2010); Vrijhoef (2011); BIS (2013b); Costin *et al.* (2014); Khalfan *et al.* (2015); Papadonikolaki *et al.* (2015a); Papadonikolaki *et al.* (2015b).
Coordination through BIM	Effective operations and resource alignment and control for the attainment of project objectives through communication, transparent and effective project data management.	
Integration through BIM	Functional coupling of fragmented CSC organisations into an integrated project delivery team(s)	

Won and Lee (2012) similarly identified several qualification type attributes that stimulate BIM delivery success. This included, experience, software expertise, organisational structures, staff (BIM manager), tools and technical support. Clearly, BIM capability criteria have been identified as a major part of BIM CSFs. Therefore, their use as qualification criteria could aid the prediction of the propensity to succeed during selection or pre-qualification.

Since the BIM CSFs were considered generically, in these studies (Won and Lee, 2012; Mom *et al.,* 2014; Tsai *et al.,* 2014) many of them cannot be considered as qualification criteria since they cannot be easily converted to assessment metrics, hence, their objective assessment may be challenging. The proposed number of CSFs are usually enormous, thus, not concise enough for qualification purposes (See Tsai *et al.,* 2014). One other key limitation of the study by Tsai *et al.* (2014) is that, success was looked at only from the point of view of value creation. The CSFs considered in these studies are also mainly related to BIM implementation success rather than delivery success on projects.

However, the similarities between BIM CSFs and capability criteria support Al-Zahrani (2013) and Doloi's (2009a) assertions that CSFs can be looked at from the perspective of qualification criteria. This brings into focus, the need to investigate the relationship between criteria used in BIM qualification and their implications on delivery success.

4.3.7 Identifying BIM Qualification Criteria

Hartmann *et al.* (2009) categorised general qualification criteria as price, technical know-how, quality and cooperation. According to Plebankiewicz (2009), the basic criteria for contractor pre-qualification should be based on their financial standing, technical ability, management capability, health and safety and reputation. Others have proposed criteria specifically for sub-contractor selection. This includes performance on previous projects, financial capacity, timely completion, labour payment, quality of production, standard of workmanship, quality of materials used, compliance with site safety requirements, compliance with contract and collaboration with other subcontractors (Holt *et al.,* 1994; Hatush and Skitmore, 1997; Arslan *et al.,* 2008; Plebankiewicz, 2009). Cheung *et al.* (2002) developed a model for selection of architectural consultants. The criteria relied upon were the background of a firm, reputation, and technical qualification, experience, past performance, capacity and methodology proposed to deliver work. These broadly highlight organisational attributes related to competence, capacity and suitability of proposed approaches to work execution. Other studies based on modern procurement tenets have advocated softer attributes like culture and collaborative ethos (Kumaraswamy and Matthews, 2000; Doloi, 2009b).

From the review of the classifications above, it is clear that qualification criteria often relate to the identification of an ability to perform. Thus, BIM capability frameworks provide a good basis for the identification of specific BIM qualification criteria for pre-qualification or selection. According to Succar *et al.* (2013), BIM capability criteria must be based on anecdotes, representative of a firm's likely performance within a BIM environment. These must reflect core competencies or an ability to deliver a measurable outcome related to BIM. Generally, attributes that relate to BIM competence, resources and historical indicators of BIM performance are suggested as appropriate in the measurement of BIM capability for purposes of selection (van Berlo *et al.,* 2012; NIBS, 2012; Kam *et* *al.,* 2013b; Succar *et al.,* 2012; 2013; Du *et al.,* 2014; Giel and Issa, 2014). From this review there is sufficient basis for the development BIM qualification criteria with reference to both construction selection studies and BIM capability studies.

4.4 DECISION SUPPORT FRAMEWORKS AND BIM QUALIFICATION

Qualifying the CSC for projects is a multi-criteria decision process and requires a structured approach to decision making (Arslan, 2012). This is to avoid the over reliance on the subjective judgement of decision makers during the process (Hatush and Skitmore, 1997). Tendering is, therefore, often based on strict criteria and approaches to evaluation (Arslan, 2012). A key component is the allocation of weights to evaluation criteria as well as guidance on how to award marks (Nieto-Morote and Rus-Vila, 2012). In order to make this exercise less daunting, DSS are often used to aid evaluators' consistency and accuracy in evaluations (Arslan *et al.,* 2008).

DSS are mainly computer-based systems that assist organisations to structure and simplify complex decision-making problems such as pre-qualification and selection. According to Mohemad *et al.* (2010) they help decision makers to structure the decision problem rather than replace decision-making processes. The construction industry is looking towards the optimisation of IT in all operations. Resultantly, many computer-based DSS programmes and spreadsheets have been developed for tendering, pre-qualification and selection (Arslan *et al.,* 2008). According to Arslan (2012), this is the most convenient and cost effective approach to enhancing decision making for tendering and selection evaluations.

A computer based DSS, QUALIFIER-1 and QUALIFIER-2 were among the early tools designed to aid decision makers in pre-qualification and selection (Russell *et al.,* 1992). Arslan *et al.,* (2008) developed a web-based tool for evaluating sub-contractor suitability (WEBSES). In a similar study, Arslan (2012) developed a web-based tool for contractor evaluation system (WEB-CONTEST). According to Arslan *et al.* (2008) the benefits of DSS for pre-qualification and selection include: faster selection process, more systematic approach to evaluation, reduction of subjectivity in evaluation, low cost and competitiveness. Similarly, most BIM capability evaluations have been developed into web applications or spreadsheets to aid decision makers in evaluating the ability to deliver BIM (NIBS, 2007; IU, 2009; CIC, 2013b; Kam *et al.,* 2013; ARUP, 2016).

DSS lend themselves to evidence-based decision making. Therefore, knowledge from empirical research can be structured into a decision support framework (DSF) for application within DSS (Mohemad *et al.,* 2010). For instance, knowledge about the impact of BIM qualification criteria on delivery success can be structured in a DSF for use within DSS that predicts the firm with the most likelihood of success in the delivery of BIM. This will include BIM qualification criteria and a description of their metrics, scoring guidance or evidence needed to attain a performance score. The framework can provide a computational method for aggregation of scores in order to choose the best candidate (see Arslan, 2012; CIC; 2012; Succar *et al.,* 2012; Kam *et al.,* 2014; ARUP, 2016).

For more practical application and wider acceptability among practitioners, it is important to rely on simple computational methods. This is easily attainable through shareable spreadsheets that can be collaboratively used through cloud-based networks. Manu (2013) produced excel spreadsheet as DSS for construction accident risk analysis during pre-construction decision making. Among other benefits, spreadsheets offer cost effectiveness, wide popularity, easy usage and accessibility (Microsoft, 2016). BIM maturity models have similarly been presented in spreadsheets (UI, 2009, CIC, 2013b; ARUP, 2016). Simple spreadsheet-based tools can also be developed, shared and accessed freely through open access cloud-based applications (Googlesheets, 2016). An openly available software that can be adopted to implement a BIM qualification DSF is Googlesheets, a Web-based application that allows users to create, update and modify spreadsheets as well as share data live online. It is an Ajax-based program and is compatible with Microsoft Excel and CSV (comma-separated values) (Googlesheets, 2016).

4.5 CHAPTER SUMMARY

From the review of literature, it has been demonstrated that success in construction is influenced by CSC capabilities or qualification. Previous studies have been reviewed, highlighting the need for an understanding of the relationship between often pre-emptive qualification criteria and delivery success. The review reveals that this can also be explored further in the BIM context. It is further demonstrated that, this can lead to more holistic BIM qualification of CSC organisations on projects based on their ability to deliver on the strategic objectives of BIM usage in the CSC. The next chapter discusses methodology and research design adopted for this study.

CHAPTER 5: METHODOLOGY AND RESEARCH DESIGN

5.1 INTRODUCTION

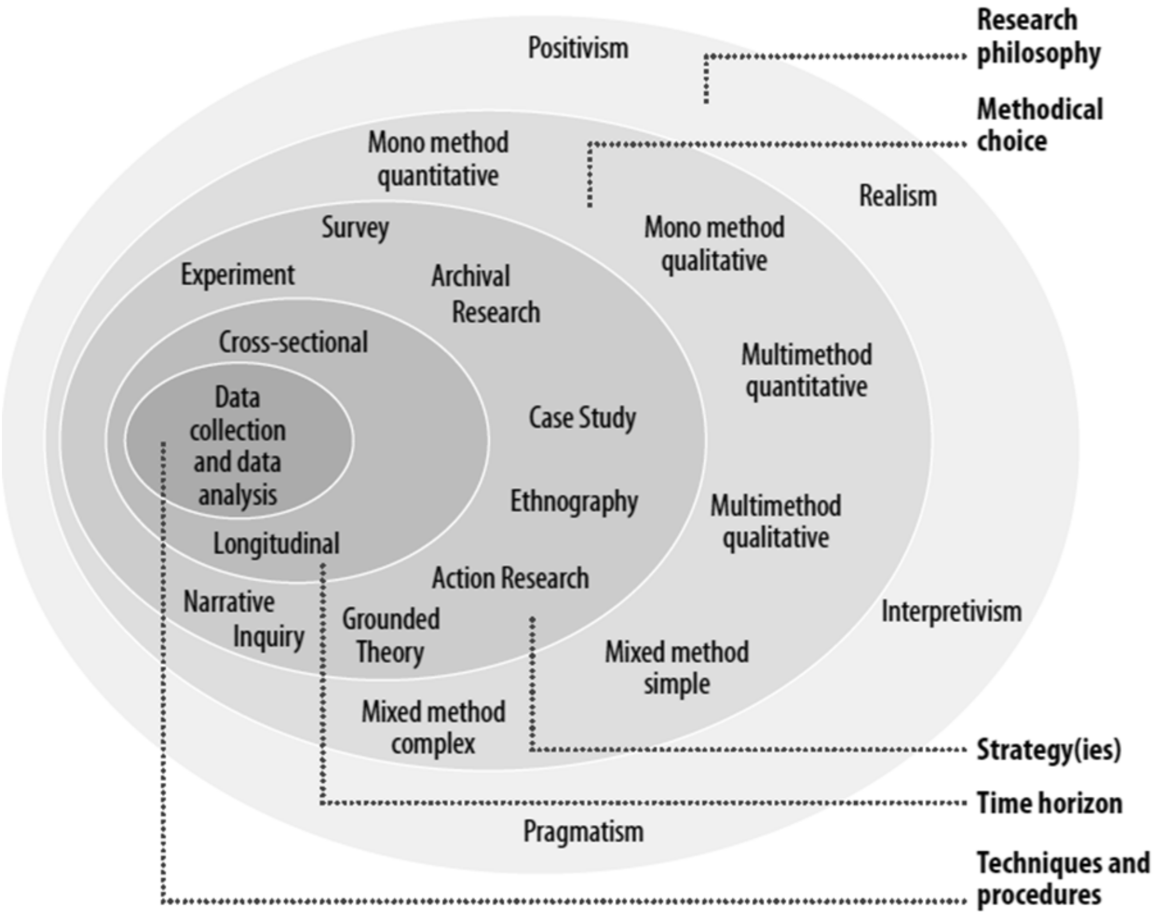
The success of academic research is dependent on effective application of available methodological techniques for investigating the research problem (Fellows and Liu, 2009). Research methodology refers to principles, procedures and logical thought processes that can be used for scientific enquiry (Knight and Ruddock, 2008). The choice of an appropriate method ensures an ethical approach to enquiry and analysis of results (Fellows and Liu, 2009). This further enhances the standard, validity of claims and conclusions to be drawn at the end of the study (Yin, 2003). Based on an extensive review of methodologies and methods, this chapter discusses the selection and justification of the most appropriate approach to answering the research questions within the study's scope and context.

Saunders *et al.* (2007) defined the research process as consisting of layers, similar to an 'onion' in structure (Figure 5.1). The main concept of this research onion is the systematic consideration of methodology and research design beginning from the outer layers right down to the innermost core. In this study, Saunders *et al.'s* (2007) classification of the layers in the research 'onion' is adopted to guide the review of possible research concepts and methodological approaches that can be applied to the study. Saunders and Tosey's (2012) classification of layers in the research onion is adopted and outlined as follows:

- **Research Philosophy:** discusses the researcher's world view on the ontological and epistemological foundations of the research;
- **Methodological choice:** discusses the different research approaches in relation to the use of quantitative method or methods, a qualitative method or methods, or a mixture of both;
- **Research Strategy:** highlights different research qualitative and quantitative strategies in relation to the answering of the research question. This includes: case study, survey,

grounded theory, ethnography, archival research, narrative enquiry and experimental strategies;

- **Time horizon:** discusses and highlights the time horizon over which the research is undertaken;
- **Techniques and Procedures:** discusses techniques and procedures engaged for data collection and analysis; and



Source: *Saunders and Tosey (2012) reused with permission from © Mark Saunders*

Figure 5.1: The Elements of Research Design

5.2 RESEARCH PHILOSOPHY

According to Creswell (2009) research philosophy generally represents the philosophical worldview that forms the basis for the conceptualisation of a research problem. It can be regarded as the *"basic set of beliefs that guide action in the conduct of research"* (Guba, 1990 p.17). The philosophical position of social research is underpinned by a number of considerations (Bryman, 2004). The philosophical position questions how we acquire knowledge as well as its acceptability to a particular field of enquiry. It, therefore, represents the understanding of the ways of seeking knowledge. According to Crotty (2003) philosophical position allows researcher to interrogate what we know and how we know. Furthermore, these considerations are regarded as the rationale for theory and the definition of validity of knowledge (Creswell, 2003). Saunders and Tosey (2013) identified four main philosophical positions in research namely positivism, realism, interpretivist and pragmatism.

Positivism Philosophy**:** This philosophical stance assumes the world conforms to fixed laws of causes and effect, and complex issues can be tackled using simplified and systematic approaches to dealing with this (Crotty, 2003). The positivist epistemology, therefore, advocates the application of methods from natural sciences to study social reality and other phenomenon (Saunders *et al.,* 2007). Principles relied on for conduct of research is viewed as generalisable and parallel to those delivered by the natural experts (Remenyi *et al.,* 1998).

Realism Philosophy**:** This philosophical stance explains logical assumption that the recognition of reality is independent of the human mind (Saunders *et al.,* 2007). According to Crotty (2003) realism is different from the concept of idealism, which describes the existence of mind and its peculiarities only. Realism, thus, poses the question of what the presence of knowledge is as well as how our understanding of this is interlinked (Saunders *et al.,* 2007).

Interpretivist Philosophy**:** This position assumes that the fundamental concept of a researcher's view should include the appreciation of the differences that exist between humans as social actors (Saunders *et al.,* 2009). This view asserts that the focus of research should be people rather than objects (Fellows and Liu, 2009).

Pragmatism Philosophy (Does Research Have to Adopt One Position?): More recently, this ardent attachment of research to any one of these paradigms in isolation has been criticised based on the perceived weaknesses, which may result from aligning any study to one paradigm. Based on this recognition, pragmatism has been proposed as an alternative to approaching social research (Morgan, 2007). According to Creswell (2009), the pragmatism philosophy is seen as the foundation of relying on more than one methodological approach to enquiry (ontology, epistemology and axiology). It must, therefore, be adapted to achieve better outcomes depending on the nature of the research question (if it is multi-dimensional).

Tashakkori and Teddlie (1998) advocate pragmatism for practical based research, where researchers must think of the adopted philosophical position as a continuum rather than opposing thoughts. They assert that pragmatism is intuitively stimulating, avoiding focus on rather mundane antagonistic positions assumed by the competing philosophical worldviews (positivist and interpretivist). Pragmatism has, however, been criticised for dealing with reality and truth rather than theory and opinion (Morgan, 2007).

5.2.1 Adopted Philosophical Position

While acknowledging the debate surrounding the various paradigms, this study adopts pragmatism as the philosophical stance for a number of reasons. The study aims to explore requirements for BIM as well as measure the impact of qualification criteria on delivery success. From a review of these objectives, it is evident that while there is a need for contextualisation of the research problem the research also requires generalisation and measurement to establish relationships. This highlights the multi-objective nature of the study which spans beyond single methodological or philosophical underpinning. It is therefore, appropriate to adopt methodologies that answer each aspect of the research objectives adequately, hence, the need for a pluralistic and practical approach to enquiry. Interpretivist philosophical positions are often associated with exploration of phenomena and will be suitable for contextualising BIM capability in research context (pre-qualification, selection, CSC and UK) as a result of lack of similar research. On the hand, the establishment of relationships between qualification criteria and success requires measurements which are mostly associated with a positivist strategies (Tashakkori and Teddlie, 1998; Creswell, 2003). Pragmatism is therefore chosen as the main philosophical position since it straddles between both positivist and interpretivist paradigms and is the most widely associated paradigm for the conduct of research that requires multiple approaches and methodologies (Morgan, 2007). Pragmatism as a philosophical stance, further, aligns with the view of complementarity in research (Chynoweth, 2006). The pragmatic approach adopted will, therefore, work to achieve consensus between the various philosophical paradigms in the design of this research (Morgan, 2007). According to Chynoweth, (2006 p.2), the built environment and construction management field is *'multidisciplinary'* and requires a *'balanced approach'* to research with full consideration of all philosophical associations of the constructs or theorem underpinning each research objective. Pragmatism is, thus, adopted as a philosophical stance for this study.

5.3 METHODOLOGICAL CHOICE

According to Crotty (2003) methodology is the plan of action, the approach, design or process behind the preference and application techniques in research. Saunders and Tosey (2013) identify three main classifications: Mono methods, which refer to techniques that rely on one of the two main methodological choices (quantitative and qualitative) in research; Multi methods and mixed methods, which rely on both methodological choices for the conduct of a single piece of research.

5.3.1 Quantitative Research (mono method)

This refers to a research method that generally relies on techniques and processes that relate to facts and figures rather than subjective opinions (Saunders *et al.,* 2007). Quantitative research is often used to describe empirical enquiry into phenomena through statistical or computational techniques (Denscombe, 2010). Empirical data is observed and measured to provide quantitative relationships. A major advantage of this approach is that the researcher develops an objective about the findings of the research (Amaratunga *et al.,* 2002).

Quantitative research, therefore, refers to testing of objective theories and sometimes prior formulations of hypotheses for subsequent testing of relationship among variables (Denscombe, 2010). It has been found to be most suitable for addressing research questions relating to what, how much and how many (Fellows and Liu, 2008). Rigidity, lack of context, inadequacy and inaccuracy of sampling techniques may, however, affect reliability of findings (Denscombe, 2010). Bryman (2004) further identified the following weaknesses, which should be considered in the design of quantitative studies in order to mitigate some of its limitations:

- lack of distinction between people and social institutions from the natural world; and
- The extensive reliance on instruments and procedures that may be difficult to associate with the natural world (Bryman, 2004).

Despite these criticisms, this approach has proved to be a widely used and accepted approach within academia, particularly in the applied sciences (Robson, 2002; Fellows and Liu, 2008). The most prominent quantitative strategies are surveys and experiment, which are discussed in the research strategies section.

5.3.2 Qualitative Research (mono method)

According to Robson (2002) qualitative methods are very effective in drawing personal, individual and group perspectives on a phenomenon being studied. It promotes a natural and spontaneous development of the enquiry (Denscombe, 2010). Qualitative research, thus, provides a means for exploring and understanding the subjective thoughts that individuals or groups ascribe to a phenomenon (Creswell, 2009). Consequently, it is associated with high levels of subjectivity problems of reliability and bias as a result of the apparent lack of boundaries (Knight and Ruddock, 2008). It is useful in answering research questions that relate to how and why (Fellows and Liu, 2008). Qualitative research approaches are regarded as more suitable in circumstances where the main research objective seeks to enhance our understanding of a phenomenon, especially when this phenomenon is deeply entrenched in its context (Knight and Ruddock, 2008; Denscombe, 2010). Bryman (2004) outlined the following criticisms of qualitative approaches:

- Impressionist and subjective because findings are usually based on unsystematic views about what is important and significant;
- Difficult to replicate because it relies on unstructured data and lacks standardised procedures;
- Difficult to generalise because of often restricted scope; and
- Lack of transparency due to associated high levels of subjectivity.

These limitations can, however, be addressed to improve reliability. Examples of how this can be achieved include cross-checking data from transcripts to ensure they do not contain mistakes. A specific definition of scope and themes for coding data during analysis could also improve reliability (Bryman, 2004; Fellows and Liu, 2008). Validity can also be ensured if themes relied on are based on convergence of several sources of data or perspectives from participants (Creswell, 2009).

5.3.3 Mixed and Multi Methods Research

This approach adopts both the qualitative and quantitative techniques in a single study. According to Creswell *et al.* (2009), such simultaneous application of more than one research technique (qualitative and quantitative) is referred to as mixed, multi or triangulation technique. Mixed method research is advocated for the conduct of research in scenarios where the nature of the problem lends itself to use of data collection methods across quantitative and qualitative methods (Amaratunga *et al.,* 2002). Therefore, if it is possible to collect both qualitative and quantitative data, then it is assumed that the analysis and conclusion could provide a more comprehensive view or understanding of the phenomenon (Creswell, 2009).

Mixed method strategies are not as popular as either the quantitative or qualitative method. The idea first emerged after successful engagement of both methods in a study to validate psychological traits by Campbell and Fisk in 1959 (Creswell, 2009). These researchers tried to eliminate the limitations of traditional strategies, through a complementary use of two or more methods (Amaratunga *et al.,* 2002). Various types of mixed methods exist depending on the way in which the strategies are integrated: either in terms of the extent of reliance on one strategy more than the other or the sequence of usage.

Multi Method Design: Refer to a type of mixed methodological design where either qualitative or quantitative are relatively complete on their own before being integrated to form conclusions (Saunders and Tosey, 2012).

Mixed Method Design: This generally refers to design where qualitative and quantitative strategies are engaged to collect data either sequentially or concurrently. The data is then integrated at one stage(s) in the research process (Creswell *et al.,* 2009).

Creswell (2009) identified three main mixed method strategies as follows:

Sequential Mixed Method: This strategy allows findings of one method to be verified by another. This may involve beginning with a qualitative strategy followed by a quantitative strategy (Tashakkori and Teddlie, 1998). This approach is referred to as a sequential exploratory design. According to Creswell (2003), this strategy can be used when there is the need for both generalisation as well as in-depth assessment. Thus, interviews could be used in an exploratory qualitative study and then followed by a wider quantitative enquiry. Exploration may help the researcher to build general knowledge about proposed variables to be studied, which may aid the development of an instrument (such as a questionnaire) and then study the variables with a large sample of individuals quantitatively through this instrument (Tashakkori and Teddlie, 1998; Creswell, 2009).

Deeper understanding of results emanating from a quantitative study could also be explored through a qualitative studied sequentially (Creswell, 2003). This approach is referred to as a sequential explanatory design. In this design, a researcher first collects and analyses the quantitative data followed by qualitative data in the second round of the sequence. This is often used to elaborate further on quantitative results obtained in the first round. One of the advantages of this approach is that qualitative analysis can be used to provide depth as well as contextualise statistical results (Creswell*,* 2003).

Concurrent Mixed Method: This approach is also referred to as the parallel or simultaneous design (Tashakkori and Teddlie, 1998). Through this approach, both qualitative and quantitative strategies are engaged simultaneously to collect data. The data is subsequently merged to provide a comprehensive understanding of the phenomenon being researched (Amaratunga *et al.,* 2002). Concurrent mixed method is advocated as a result of shorter data collection time due to the parallel nature of data collection (Creswell, 2009). The findings are generally regarded as well-validated but the resources need to conduct it may be enormous (Tashakkori and Teddlie, 1998). Challenges may also arise in finding an appropriate method of integrating the diverse data during analysis (Tashakkori and Teddlie, 1998; Creswell, 2009).

Transformative Mixed Method: This strategy allows the researcher to rely on a dual theoretical lens within which quantitative and qualitative data could be deployed. Such a theoretical perspective could be ideological and involve either sequential or concurrent approach (Creswell, 2009). There, however, remains minimal guidance on this strategy, hence, lack of popularity within the mixed method research community (Creswell, 2009).

5.3.4 Methodological Choice for Study

Methodological pluralism encourages the use of multiple methodological approaches (Amaratunga *et al.,* 2002; Chynoweth, 2006). Therefore, is proposed as an appropriate research method to break the barriers of limited literature and data sources due to the novelty of BIM as a research area. Furthermore, the adoption of a pragmatic philosophical stance makes mixed methods a natural choice for this study. Pragmatism is the associated paradigm for the conduct of mixed method research (Creswell, 2007). Secondly, it focuses on adoption of the most appropriate research strategies that answer each aspect of the research question adequately, hence, its pluralistic and practical nature (Amaratunga *et al.,* 2002). A sequential exploratory mixed method research strategy is adopted. This allows the exploration of concepts through qualitative methods subsequent testing of assumptions in quantitative study.

Exploration of research propositions in the first instance, is important when dealing with novel concepts such as BIM where established theories are scarce (Adriaanse, 2007). As a result this assertion some BIM studies have exclusively relied on qualitative methods (Adriaanse, 2007; Navendren *et al.,* 2014; Sackey, 2014). This study aims to understand qualification in the BIM context, thus aligns with the views of Adriaanse (2007) that qualitative studies are more suited to provide depth and context. Furthermore, the study aims to establish the relationship between qualification criteria and success. The establishment of such relationships have however been achieved mainly through quantitative methods (Doloi, 2009a; Doloi, 2009b; Al-Zahrani and Emsley, 2013). Thus, in order to achieve the research objectives the sequential exploratory mixed research method is the most appropriate.

5.4 RESEARCH STRATEGIES

Research strategy refers to the overall logic underpinning the collection of evidence to support an enquiry (Yin, 2003). Bell and Opie (2002) suggested five types of research strategy: action research, ethnography, surveys, case studies, and experimental research. Saunders and Tosey (2012) refer to three additional strategies: grounded theory, archival research and narrative enquiry. Fischer and Wertz (2002) also refer to phenomenology as a research strategy. These strategies may be adopted as part of selected research methods including exploratory, explanatory or descriptive research (Yin, 2003). According to Saunders *et al.* (2007) the choice of research strategy is often dependent on the nature of the research question or objectives. Other influencing factors on the choice of strategy may include the extent of existing knowledge on the strategy, familiarity or resources needed by the researcher (Robson, 2002; Saunders *et al.,* 2007).

The various strategies are also based on different philosophical underpinnings, thus, the philosophical stance of research influences the choice of strategy. A review of the most widely adopted research strategies is presented below.

5.4.1 Experiments

This is the research strategy that relies on the manipulation, control and testing of defined variables to understand inter-tendencies and causal relationships (Fellows and Liu, 2008). This strategy often relies on manipulation of an independent variable to identify an extent of relationship predefined by dependent variables (Kumar, 2011). Experimental research is more popular among natural sciences and medical research (Fellows and Liu, 2008; Kumar, 2011). One of the primary objectives of this strategy is the attainment of objectivity, resource predictability, validity and replicability (Saunders *et al.,* 2007). This approach could, however, be unpredictable in terms of its demands on time (Kumar, 2011).

5.4.2 Surveys

This is a research strategy often used to establish the status of a phenomenon among a group (Robson, 2002). It is largely premised on the mathematical and scientific logic that patterns identified within a representative small group is reflective of a general situation (Forza, 2002). Thus, statistical sampling is often engaged to identify a sample within a general population to be surveyed (Robson, 2002). Characteristics of such a sample are often regarded as proxy for generalisation across similar traits in the wider population (Knight and Ruddock, 2008). The survey strategy is advocated for scenarios where contemporary data is required within an area such as geographically dispersed contexts (Bryman, 2004). According to Yin (2003) surveys are appropriate for the exploration of relations between personal or perception based variables. Surveys could also be used for descriptive or explanatory research. The mode of data collection and sampling of participants are important determinants of survey data validity (Bryman, 2004).

5.4.3 Archival Research

The archival research strategy involves review and extraction of evidence from archival records (Elder *et al.,* 1993). Archival records include data held within institutional repositories or other types of repositories for storing records (Foster and Sheppard, 1995). A key source of archival data is government institutions (Scott, 1990). Some other sources include businesses and family records (Hill, 1993). Archival data may include accumulation of data from life activities of transfer of stored historical data (Elder *et al.,* 1993). Such data is often studied in order to identify patterns that have formed over time. Two main forms exist: primary archival research and secondary archival research (Scott, 1990; Elder *et al.,* 1993). These respectively refer to empirical investigation from the main sources of the data related to the phenomenon being studied or the consultation of secondary sources either through online or other related data.

5.4.4 Case Study Research

Case studies are used to develop an in-depth understanding of a phenomenon (Yin, 2009) This is often conducted within a defined context called the case, which may refer to a specific set or restricting attributes, such as a geographic location, institution or organisation (Fellows and Liu, 2008). The studies are often performed within a defined time limit, where detailed information about the phenomenon is collected and analysed (Yin, 2009). The phenomenon studied within case study research may include programmes, events, activities and practices of individuals or groups of people, typically, using a variety of data sources and procedures (Knight and Ruddock, 2008). Yin (2009) provides a useful treatise on the design and implementation of case study strategy. This approach is advocated for investigating a single instance or event to great detail (Yin, 2009). Case studies focus on the investigation of a small number of cases rather than large number of cases (Fellows and Liu, 2008). Proponents of this strategy advocate its usage where the focus of the study is to understand rather than quantify variables (Kumar, 2011).

5.4.5 Ethnography

The primary character of ethnographic studies is the direct interaction of the researcher within the natural setting of the research subjects over often long periods of time (Creswell, 2009). During this time, observational data is often collected (LeCompte and Schensul, 1999). This strategy allows the researcher to directly observe rather than use perceptions or answers from participants (Creswell, 2007). It is, therefore, appropriate for the study of phenomena that can be easily observed such as practices or behaviours (LeCompte and Schensul, 1999). Ethnography is also considered an in-depth approach of inquiry as a result of the often long period within which researchers embed themselves within the cultural setting of the research (Creswell, 2009). Ethnography offers high levels of flexibility due to ability of subject to change the approach in response to requirements of the environment within which the study is conducted (LeCompte and Schensul, 1999). It requires longer times to conclude as well as high degree of observation and qualitative research skills.

5.4.6 Action Research

This refers to research within a practical setting with the aim of integrating action and reflection, theory and practice in solving a research problem (Coghlan and Brannick, 2005; Cameron and Price, 2009). A key characteristic is the development of practical approach to the discovery of knowledge for direct application (Reason and Bradbury, 2008). The action approach usually involves an 'insider' who collaboratively engages the rest of a system, such as an organisation, to reflect on existing practices or knowledge towards improvement (Cameron and Price, 2009). It is, therefore, popular for research within industrial or organisational settings where there is a need for understanding or improving a process (Coghlan and Brannick, 2005; Saunders *et al.,* 2007). The time requirements could, however, be excessive (Reason and Bradbury, 2008).

5.4.7 Grounded Theory

The primary objective of grounded theory is the development of theory from an inquiry (Creswell, 2009). This includes in-depth evaluation of processes, actions and behaviours of subjects (Strauss and Corbin, 1990). The perceptions and views could further provide basis for the development of a new way of thinking about phenomena that forms the basis for theory development (Creswell, 2009). Grounded theory often involves collection of multiple sources of data as well as fine grained analysis (Strauss and Corbin, 1990).

5.4.8 Narrative Research

This is a qualitative strategy, where individual life styles are studied through story telling from their own perspective (Creswell, 2009). The stories are then reorganised and presented in a chronological order (Clandinin and Connelly, 2000). The researcher combines their own experience and perspective in retelling the story narrated by the subject(s) (Clandinin and Connelly, 2000). Biographies and autobiographies are usually written in this manner.

5.4.9 Phenomenological Research

Phenomenological research is a strategy that involves the study of the ways a person's world view is formed in part by the person who lives it (Fischer and Wertz, 2002). *'Lived experience'* of participants is, therefore, of the greatest interest to phenomenologists (Van Manen, 1990). This strategy is therefore appropriate where the personal experiences of individuals about a phenomenon are required to answer research questions (Creswell, 2009). Researchers must, however, be as remote as possible from this experience, thus, phenomenology encourages the use of open ended questions (Fischer and Wertz, 2002).

5.4.10 Adopted Research Strategies

Based on the pragmatic philosophical stance and mixed methodological choices, two main research strategies were adopted for the qualitative and quantitative phases, respectively. 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 qualification criteria based on their experience of working on construction projects. Similar methods have been applied in the exploratory phase of mixed method research (Manu, 2013). A survey research strategy is also adopted to enable investigation of research propositions from the earlier phases among a wider group of respondents. This will be the overarching strategy for the quantitative phase of the research. Surveys are the most associated strategy with the conduct of quantitative research including several BIM studies (Newton and Chileshe, 2012; Davies and Harty, 2013; Kam *et al.,* 2014; Smits *et al.,* 2016).

5.5 RESEARCH TIME HORIZON

Time horizon represents the length of the period within which the research is conducted (Saunders and Tosey, 2012). It mainly consists of two categories: longitudinal where research is conducted over long periods of time to see evolution of a phenomenon; or cross sectional, where it considers phenomena at a particular point in time (Robson, 2002; Saunders and Tosey, 2012). The choice, therefore, is dependent on the research question or objectives and the extent to which they can be answered within a particular allocation of time (Saunders *et al.,* 2007). Examples of approaches often used on longitudinal studies include experiment, action research and grounded theory. While cross sectional often involve surveys (Saunders and Tosey, 2012).

5.5.1 Time Horizon for Study

This study is generally a snapshot, hence, cross-sectional in nature (*ibid*). Data collected was data required to answer the research question at a particular point in time and did not require the continuous investigation of its evolution. Data collection commenced in September 2013 for the first phase, January 2014 for the second phase and August 2014 for the final phase.

5.6 TECHNIQUES AND PROCEDURES

This refers to techniques that will be engaged to collect data. According to Kumar (2011) there exist three main types, observations, questionnaires and interviews. Naoum, (2007) also classified surveys as a data collection technique. This has, however, been discussed based on Saunders and Tosey's (2012) classification as a research strategy. The choice of a mode or type of data collection depends largely on the aim as well as research strategy (Naoum, 2007). However, these techniques can be used across many strategies, though they might be more suitable to some cases than others (Fellows and Liu, 2008). The accessibility or availability of the data could also inform the type of technique to be used (Naoum, 2007).

5.6.1 Interviews

According to Saunders *et al.* (2009), interviews are important when collecting data based on perceptions or knowledge of individuals or groups. Generally, interviews are regarded as appropriate where data is complex and requires detailed description or narratives from interviewees (Robson, 2002). They allow a more in-depth interrogation of responses, with the opportunity for the respondent to seek clarification of the questions asked, and to expand on their own responses. The likelihood of interviewer's bias is, however, very high (Denscombe, 2010).

There are three main categories of interviews: structured interviews, semi-structured interviews, and unstructured interviews (Robson, 2002).

Structured interviews: This approach uses questions that are set and related to answering the research question or objectives (Denscombe, 2010). They allow a structured approach to asking predetermined questions to which specific types of answers will be given (Thomas, 2002). Answers will, therefore, largely remain within this predefined scope. This approach is suitable where the research objectives are well defined from the beginning (Robson, 2002).

Unstructured interviews: On the other hand, this approach relies on open ended questions to which interviewees are allowed the flexibility to elaborate in an unrestrictive manner (Denscombe, 2010). Predefined questions are not used as the questions may rather emerge from answers being given by interviewees (Thomas, 2002). Thus, both interviewer and interviewee have some degree of control over the process (Saunders *et al.,* 2009). The general concept and scope will, however, need to be known in order to prevent total deviation.

Semi-structured interviews: Is an approach that incorporates features of both structured and unstructured interviews (Denscombe, 2010). Predefined questions are relied on but not to a great extent as interviewees are given more freedom to discuss further (Thomas, 2002). The questions, therefore, typically are both closed and open ended (Saunders *et al.,* 2009).

5.6.2 Questionnaires

They allow information to be collected from respondents and still maintain the desired anonymity producing results that are easy to compare and analyse (Denscombe, 2010). A questionnaire consists of a list of questions to which respondents are required to provide answers (Kumar, 2011). It is designed such that all respondents will have a similar understanding of requirements for responses (Robson, 2002). Responses could be open ended or closed ended sometimes including multiple choice options from which respondents will choose. Types of questionnaires include self-administered, interview-administered, internet mediated questionnaires, postal questionnaires, and delivery and collection questionnaires (Fellows and Liu, 2008). Each type of questionnaire has specific advantages and disadvantages that guide their choice in view of which suits the research context (Knight and Ruddock, 2008). For example, internet mediated questionnaires are considered easy as a result of proliferation of internet technology, which makes it cheaper and faster to administer. Several applications have also emerged that support automatic collation and analysis of responses (Dillman, 2007; Saunders *et al.,* 2007). When interview questionnaires are used, the respondents may be asked to clarify some responses for more in-depth understanding. This approach and other self-administered approaches are, however, time consuming and may be expensive if respondents are geographically dispersed (Oppenheim, 1992). Saunders *et al.* (2007) discussed five factors that influence the choice of a specific questionnaire type: characteristics of the respondents; extent to which specific people need to respond; extent to which responses must not be subject to distortion; sample size; type and number of question to be asked. Other key factors that influence the choice of questionnaire include time consideration and cost (Oppenheim, 1992; Robson, 2002).

5.6.3 Observation

Observation is often used for in-depth study of social behaviour through selective approach to listening or observing phenomenon by a researcher (Bryman, 2004). Observation is described by Kumar (2011) as a purposeful and systematic approach to observing the interaction within a phenomenon. This may include human participants, whose behaviour or practices will normally be observed following guidelines called observation schedules. According to Bryman (2004) observations could be categorised as structured or unstructured depending on the nature of the schedule and the type of observations required. Structured observation allows the researcher to observe behaviour based on systematic predefined rules (Kumar, 2011). Conversely, unstructured observation would normally not follow any predefined rules but rather a general observation of behaviour after which patterns could be drawn from the analysis (Kumar, 2011). Structure of observations is similar to interviews or questionnaires with the main difference being that participants do not directly respond. The researcher collects data from their own observation of happenings. Factors that influence the type of observation include complexity of the interaction and the type of population being observed (Kumar, 2011). This method is often engaged in qualitative and behavioural research (Bryman, 2004).

5.6.4 The Delphi Technique

The Delphi technique was developed by Dalkey and Helmer (1963) as a method for achieving convergence of opinion among groups of people. Experts within Rand Corporation were engaged in iterative group decision making through elicitation of their expert opinion. It has been a preferred method for achieving consensus on knowledge about a particular subject through the engagement of experts within that field. The Delphi technique is premised on the basis that, *"two heads are better than one*" (Dalkey, 1972, p. 15). Delphi technique is, therefore, regarded as a group decision making process where controlled communication is used to collate expert opinion about a subject, through iterative process where group opinion is fed-back (Sourani and Sohail, 2014).

Delphi has been extensively applied in research with various forms of research methods, strategies or design. Some have referred to Delphi as a research method (Crisp *et al.,* 1997). Wang *et al.* (2004) refer to Delphi as a research strategy while Arditi and Gunaydin (1999) refer to Delphi as a type of survey. The consideration of Delphi as procedure or technique for data collection is however widespread (Snyder-Halpern *et al.,* 2002; Broomfield and Humphries, 2001). While there remains no universal viewpoint on the aspect of methodology that fits the Delphi philosophy it remains clear that it revolves around strategy or data collection techniques, from Saunders *et al.s'* (2007) categorisation of layers of research methodology. Thus, in this study, Delphi is regarded as a technique following Snyder-Halpern *et al.* (2002).

The main characteristics and features that differentiate Delphi as a technique are: '*anonymity*' as a result of remote communication; '*iteration'* as a result of the repetition of several rounds of data collection; '*controlled feedback'* where results of each round are presented to participants to review before commencing another round; and the *'statistical aggregation'* of group response to measure a level of agreement (Mullen, 2003; von der Gracht, 2012).

Other Group Consensus Techniques: Other available group consensus techniques include Nominal Group Technique (NGT), Interacting Groups and Staticised Groups. These are reviewed below.

- *Nominal Group Technique (NGT):* The nominal group technique (NGT) relies on a small group brainstorming session to reach consensus with the aid of a moderator (Hallowell and Gambatese, 2010). The main difference and disadvantage to Delphi technique is the need for face-to-face interaction, which has both logistical and methodological constraints related to bias (Rowe and Wright, 1999).

- *Interacting Groups:* This is a type of focus group, and like the NGT, it relies on gathering experts either in one physical location or through some telecommunication device (Powell, 2003). Like NGT, the logistical constraint of gathering experts, possibility of bias influence and lack of anonymity makes Delphi preferable (Hallowell and Gambatese, 2010).
- *Staticised Groups:* This method adopts a similar procedure to the Delphi technique with the elimination of a feedback stage and iterations (Hallowell and Gambatese, 2010). This method is advocated where feedback is considered not important. However, in this study, feedback is regarded important because reflection on responses after evaluation of the viewpoint of other experts within different scopes of practice will be vital in attaining better consensus. The suitability of these techniques in comparison with Delphi is presented in Table 5.1.

Table 5.1: Delphi compared with Other Group Techniques

Technique / Desirable Feature	Feedback	Anonymity	No need for Interaction	Iteration
Delphi Technique	Yes	Yes	Yes	Yes
Straticised Group Technique	No	Yes	Yes	No
Interacting Group Technique	Yes	No	No	No
Nominal Group Technique	Yes	No	No	Yes

5.6.4.1 Application of Delphi in Construction Research

Despite relatively lower use of Delphi within construction management studies it is gaining popularity, as advocated for decision making related research (Hallowell and Gambatese, 2010). The reviewed studies include determination of similar and relevant applications including contractor selection criteria (Hatush and Skitmore, 1997), as well as BIM competence prioritisation for owner organisations (Giel and Issa, 2014). Hallowell and Gambatese (2010) further provided guidelines for eliminating methodological weaknesses, including bias through appropriate use of statistical techniques for consensus measurement. Some other studies have adopted Delphi in investigating various phenomena within construction. A review of Delphi applications in construction research is summarised in Table 5.2.

Table 5.2: A Review of the Application of Delphi in Construction Research

Publication	Area of Construction Applied to	Rounds	Panel size	Feedback and Method of Consensus
Sourani and Sohail, (2014)	Case studies of benefits to construction research	N/A	N/A	N/A
Giel and Issa (2014)	Identification and prioritisation of owner competence in BIM	3	21	IQR
Hallowell and Gambatese (2010)	Review of usage within construction engineering and management research	N/A	N/A	N/A
Dikmen *et al.* (2010)	Prioritisation of business failure risk of construction firms risk	2	3	AHP Consistency Ratio
Ke *et al.* (2010)	Identification of Public Private Partnership risk on construction projects in china	2	46	Mean, Kendall's concordance (W)
Manoliadis *et al.* (2009)	Prioritised qualification based criteria for contractor selection through two (2) rounds of Delphi survey.	2	12	Mean
Yeung *et al.* (2009)	Determine KPI for partnering procurement performance	4	31	Mean and Kendall's Coefficient of Concordance (W).
de la Cruz et al. (2006)	Categorise risks on construction projects	1	20	Mean standard Deviation
Manoliadis *et al.* (2006)	Examined the drivers for sustainable construction in Greece through two rounds of Delphi survey.	2	20	Mean
Gunhan and Arditi (2005a)	Identification of factors affecting international construction	2	12	Mean Standard Deviation
Gunhan and Arditi (2005b)	Identification of factors affecting construction firm expansion	2	12	Mean, Standard Deviation
del Caño and de la Cruz (2002)	Categorise risks on construction projects	1	20	N/A
Chan *et al.* (2001)	Selection of Procurement method for project	4	10	Kendall's Coefficient of Concordance (W).
Arditi and Gunaydin (1999)	Perceptions of process quality in building projects	3	14	Mean, Standard Deviation
Hatush and Skitmore (1997)	Criteria for contractor selection	3	8	Qualitatively Decided

5.6.4.2 Advantages of Delphi Surveys

The Delphi survey technique has various advantages and compensates for some weaknesses of traditional survey techniques. These include reliability, validity and general quality of data collected from Delphi which often involves knowledgeable and willing participants considered to possess expert views about the subject under investigation. A summary of the advantages of Delphi has been outlined in Table 5.3 (Okoli and Pawlowski, 2004).

Table 5.3: Advantages Associated with the Delphi Technique (Okoli and Pawlowski, 2004)

Representativeness of sample	The queries addressed by a Delphi study are of a highly doubtful and speculative nature of sampling. For this reason, a general population might not adequately and correctly answer the questions.
Sample size for statistical power and significant findings	To achieve an accord among experts, group dynamics is used to determine the Delphi group size. This size is not derived from statistical power. Therefore, 10 - 18 experts are recommended by the literature for a single Delphi panel.
Reliability and response revision	In the Delphi method, although pretesting is a vital reliability reassurance measure, still test-retest reliability is irrelevant. This is because the researchers anticipate respondents to modify their answers.
Construct validity	Delphi technique can perform extra construct validation by requesting the professionals to authenticate the researcher's version and classification of the variables. This validation practice is possible as unlike many surveys, Delphi is not anonymous to the researcher.
Anonymity	Participating experts are anonymous to each other but always known to the researcher. This allows researchers to communicate with them for additional explanations.
Non-response issues	Generally in Delphi surveys, there are very little chances of non-response as most researchers have attained declaration of participation in person.
Richness of data	Traditional surveys undergo richness issues while Delphi studies essentially supply richer data due to their numerous iterations and their response review due to feedback. Also, the experts taking part in Delphi are positive towards follow-up interviews.

5.6.5 Adopted Techniques and Procedures

In this study, data was collected through interviews, questionnaires and the Delphi technique. This follows the suitability of these techniques in satisfying the exploratory mixed method approach adopted. Interviews are the most widely used technique for qualitative data collection (Robson, 2002). This choice is, therefore, in consonance with the phenomenological principles relied on for the first phase the exploratory mixed method approach adopted. The semi-structured interview approach is adopted as this allows some pre-formulations of ideas from the literature to guide the data collection process (Thomas, 2002).

The questionnaire technique was used to collect data in the quantitative aspects of the study. The questionnaire technique was applied in conjunction with the Delphi technique as part of the survey strategy adopted. The quantitative phase was in two parts in line with the sequential mixed methods approach. The first part involved the use of the Delphi technique to survey the opinion of a representative group of experienced practitioners. The second involved the traditional use of questionnaires in a survey of a wider group of industry practitioners in order to test propositions from the earlier phases. Questionnaires are the most widely used technique associated with quantitative research (Denscombe, 2010). The Delphi technique adopted allowed a quantitative approach to determining the most relevant criteria to be explored from the qualitative phase of the research. The hybrid epistemological status of Delphi, makes it both positivist and interpretivist in nature (Powell, 2003), therefore, suits the broader pragmatic philosophical stance of this study. Typically, contractor evaluation in itself is undertaken by a few experienced people, thus, the use of an expert data collection technique such as Delphi is a natural choice. Since the Delphi techniques offers opportunity for feedback, it was deemed as most appropriate for initial validation of interview findings before carrying out the general survey.

5.7 OVERALL RESEARCH DESIGN

Research design can be referred to as the master plan adopted upon identifying the appropriate approaches within the layers of research methodological design (Thomas, 2002). Yin (2003) describes the research design process as a logical plan for navigation through the research journey. Research design is, therefore, the general plan for successfully answering research questions after the identification of research philosophy, methods, strategies and techniques (Creswell *et al.,* 2003). In this study, a pragmatic, sequential exploratory mixed methodological research strategy is used to provide both breadth and depth in understanding the requirements of BIM qualification. Thus, both quantitative and qualitative methods are used to ascertain this in a sequential exploratory mixed methodological design. Semi structured interviews, a Delphi survey as well as a traditional questionnaire survey are used to address the research objectives as shown in Table 5.4.

Table 5.4: Strategies Chosen to Address Research Objectives

Strategy	Target Audience	Research Objective
Interviews (and Literature)	BIM Experts (*n*=8)	Identify and categorise BIM qualification criteria (Objective 1 and 2)
Delphi Survey	Practitioners with BIM Experience (*n*=25[30])	Identify the most critical BIM qualification criteria (Objective 3)
Traditional Surveys	Performance Appraisal of Firms on BIM-enabled Projects (*n*=64)	Ascertain the contribution and impact of each qualification criteria on BIM delivery success (Objective 3 and 4)
Framework Development		Develop and validate decision support framework (DSF) (Objective 5)

The relationship between the elements in the research design and objectives of the study is presented in the Figure 5.2.

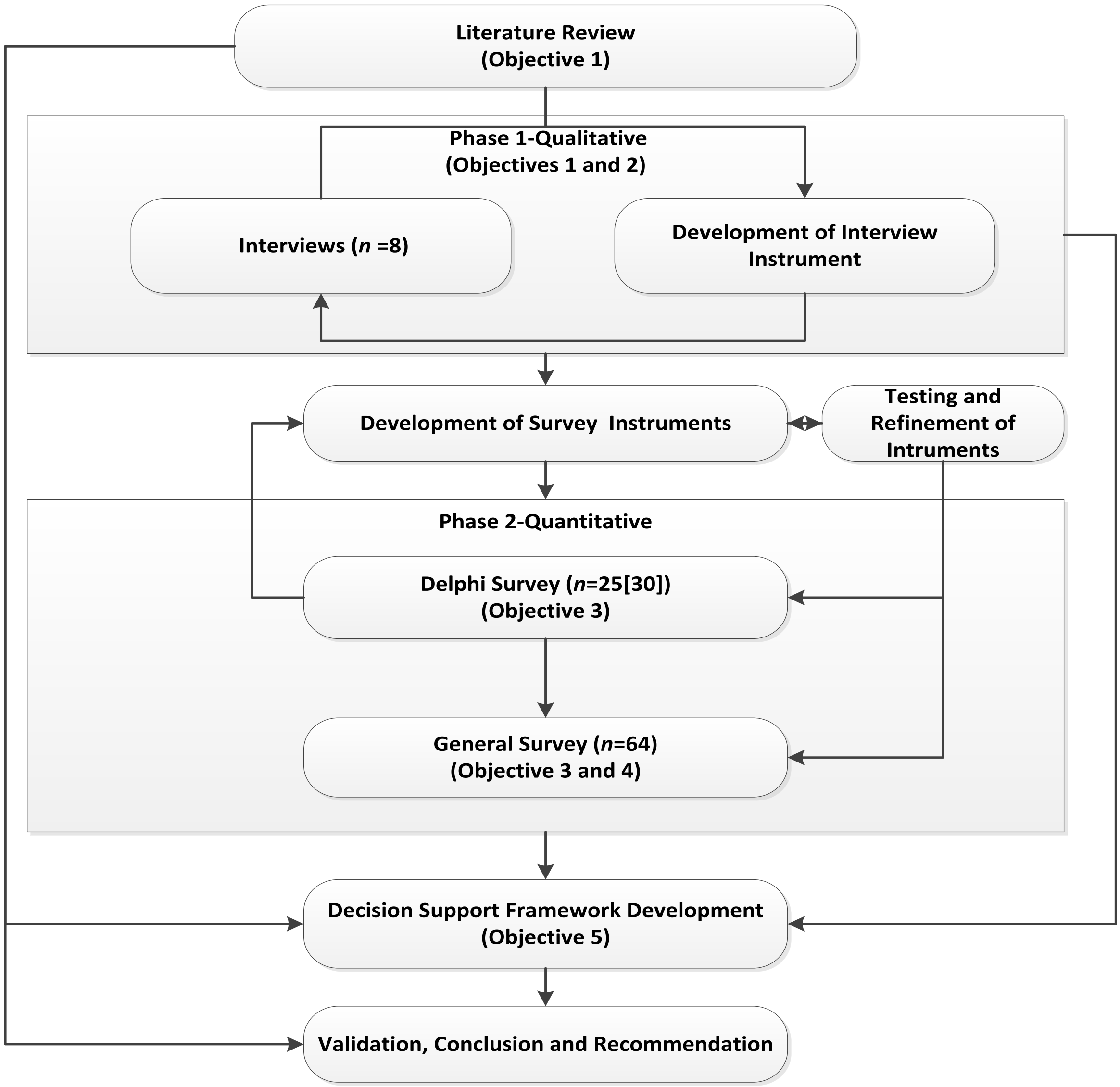


Figure 5.2: Methodological Flow Chart of Methods used in Study

5.7.1 Phase 1: The Qualitative Enquiry (Interviews)

Semi-structured interviews were conducted with BIM experts to explore relevant BIM qualification. This was to solicit their expert opinion about BIM qualification criteria that are currently being used or need to be used for CSC pre-qualification and selection. The interview procedure, analysis and results are presented in the next chapter.

5.7.2 Phase 2: The Quantitative Enquiry (Surveys)

Delphi Survey: Delphi survey was used to identify the most critical among the proposed BIM qualification criteria identified from the interviews. This was distributed across a larger number of practitioners with BIM and CSC procurement experience. Since the Delphi technique offers opportunity for feedback, it was deemed as most appropriate for initial validation of interview findings before carrying out the general survey. It also ensured that a parsimonious set of qualification criteria was used in the general survey. The development of the Delphi survey instrument, method of analysis and results is presented in Chapter 7.

General Survey: A survey was subsequently deployed to examine the relationship between BIM qualification criteria and delivery success. The survey was used to solicit the opinion of a larger group of practitioners on BIM-enabled projects in the UK. The instrument was developed from the findings of the Delphi survey. The survey procedure, method of analysis and results are also presented in Chapter 7.

5.8 ETHICAL CONSIDERATIONS FOR RESEARCH

Ethics remains very important in protecting the integrity of research (Robson, 2002; Knight and Ruddock, 2008). The dignity, privacy and confidentiality of all participants were considered highly important in this study. A number of steps were taken to achieve this. Research was designed and conducted with full consideration of the ethical requirements for the conduct of post-graduate research in The University of the West of England, Bristol (UWE). Ethical approval was, thus, sought before the collection of data from the Faculty of Environment and Technology Ethics Committee.

Participants were briefed about the background, purpose and objectives of the research through Information sheets detailing the aims and research procedure. Data was completely anonymised with no use of identifiable personal details of any of the research participants. Consent forms were attached to interview protocol and questionnaires to solicit participants' consent and willingness to participate. This included making participants aware of their rights such as withdrawal and nondisclosure of personal information. Ethical consideration for the entire research conformed to a checklist of UWE for conduct of research. Research information sheets and consent forms are attached in Appendix A of this thesis.

5.9 CHAPTER SUMMARY

The success of any research is dependent on the adoption of the right methodologies. Research methodology refers to the principles, procedures and logical thought processes that can be used for scientific investigation. The proposed methodology and design for this study have been presented and discussed. Based on pragmatic philosophical views, a sequential exploratory mixed methodological research design is adopted. The research consists of a qualitative phase where interviews are used to solicit expert opinion on BIM qualification criteria. This is followed by Delphi and general surveys of practitioners to identify critical qualification criteria as well as examine the relationship between criteria and delivery success. The next chapter presents the analysis and results of the first phase (qualitative enquiry) of this study.

CHAPTER 6: ANALYSIS AND FINDINGS FROM QUALITATIVE ENQUIRY

6.1 INTRODUCTION

This chapter discusses the analysis of data and results from the first phase (qualitative interviews) of the research design. The early part of the chapter discusses the procedure adopted for the interviews. The second covers the presentation of findings. The results consist of interviewee's opinions about the importance of BIM qualification and a proposal of a set of BIM qualification criteria.

6.2 THE INTERVIEW PROCEDURE

The main objective of the qualitative phase of this study is to explore BIM qualification criteria for selecting CSC organisations on BIM-enabled projects. Interviews were, therefore, undertaken to develop an understanding of the relevant attributes that indicate a CSC firm's BIM utilisation capacity or suitability for projects. Furthermore, interviews with experts currently implementing BIM on projects were done to aid the categorisation of BIM qualification criteria in order to develop a hierarchy of assessment criteria for CSC pre-qualification or selection purposes.

Since interviewing is embedded in an interpretive philosophical stance, the qualitative interviewing in the research offered fluidity and enabled effective contextualisation of issues (Knight and Ruddock, 2008). Interpretivism is premised on the ontology of subjective reality, where humans are social actors and interpret the world around them based on personal beliefs and values (Fellows and Liu, 2008). These subjective experiences as well as unique circumstances which surround participants' interpretation of reality provide depth to the topic under study (Thomas, 2002). In addition interviews were used in the initial stage of the research because they are better positioned to aid inductive development of consensus on novel concepts like BIM (Adriaanse, 2007). The interviews also provided an opportunity to ignore priori ideas about BIM capability in order to draw on the knowledge and experience from experts about appropriate BIM qualification criteria. This aided identification of criteria nomenclature that is more intuitive to the pre-qualification and selection process. It was necessary to develop an interview protocol and the identification of suitable participants, in order to achieve the objectives of the study. This is presented in the following sections.

6.2.1 Development of Interview Protocol

Semi-structured interviews were conducted using an interview schedule (Appendix B) containing questions and cues to guide the interviewing process. This schedule was primarily used as a guide, however, interviewees were allowed to respond freely as well as raise new issues. The interviewer was at liberty to probe further as well as ask questions emerging from responses. The schedule was in three sections. The first section asked questions about the interviewee's background. The second section focused on the importance of BIM qualification and the interviewee's awareness and use of BIM capability frameworks and tools. The final section sought interviewees' opinion about appropriate BIM qualification criteria for CSC pre-qualification and selection.

6.2.1.1 Selection of Participants for Interviews

As cited by Denscombe (2010), decisions on selecting research participants can be as precise when based on familiarity and good judgment. Participants for qualitative interviews are usually chosen based on the depth of their knowledge and experience about the phenomenon under investigation (Robson, 2002). A purposive approach was adopted to select participants with a good understanding of the subject area. Construction professionals in management roles on projects where BIM has been engaged or within organisations known to use BIM were identified as the most likely to provide useful insight. As a result, the principal parameters used in qualifying interviewees were extensive construction industry experience as well as holding a management role in BIM implementation in the UK construction industry.

Preliminary enquiries about major BIM-enabled projects within the UK were solicited from internet searches, published case studies and industry events. The events attended in order to solicit participation included conferences, workshops and talks by the following organisations between

March 2013 and August 2014: National BIM Standards (NBS), BIM Hubs UK, RICS, RIBA, CIC, Chartered institute of Civil Engineering Surveyors (CICES), Autodesk, IEEE, Association of Construction Management Researchers (ARCOM), Wessex Institute of Technology and International Council for Building (CIB). Invitations were extended to over 20 professionals who met the interviewee selection criteria within organisations and institutions at the forefront of BIM implementation in UK. Similar methods have been employed in the recruitment of interview participants in construction management research (Manu, 2012; Sackey, 2014).

Subsequently, semi-structured interviews were conducted with the eight construction professionals with an average of 16 years industry experience. These individuals were well experienced and deeply involved with BIM implementation within the organisations they represented. The interviews lasted between 30 to 40 minutes on average and were transcribed verbatim for subsequent analysis. Eight interviews for an exploratory phase of research were deemed adequate since no significantly new ideas were being raised by between the sixth and eight interviews (Guest *et al.,* 2006; Manu, 2012). The background of interviewees is presented in Table 6.1.

Table 6.1: Background of Interviewees

Interviewee ID	Role/Job Description	Experience in Construction (Years)	Experience in BIM/Related Digital Construction Technologies (Years)
1	Building Design Manger	21	21
2	Senior Commercial Manager	26	3
3	Digital Engineer	10	3
4	BIM Manager	13	6
5	Managing Quantity Surveyor	17	10
6	Senior Quantity Surveyor	12	3
7	Design Manager	15	5
8	BIM Manager	20	5

6.2.2 Analysis of Interview Data

According to Saunders *et al.* (2009), qualitative data analysis involves the interrogation of data to interpret the knowledge, opinions and experiences of interviewees in relation to key research objectives. A number of approaches have been proposed for qualitative data analysis. This includes content analysis, thematic analysis and grounded theory (Thomas, 2002; Creswell, 2009; Saunders *et al.*, 2009). The most widely used method for phenomenological based studies is thematic analysis (Thomas and Harden, 2008). According to Creswell (2007), this approach allows systematic data structuring in order to adduce patterns relevant to answering the research question.

Based on the phenomenological principles on which this stage of the research was based, thematic analysis which offers flexibility for unearthing themes that deepen the understanding of topics which have not been adequately explored (Thomas and Harden, 2008) was adopted. This was found suitable for analysing the data for this study in relation to the use of BIM capability criteria for pre-qualification and selection in the CSC context. The following recommended steps for interview thematic analysis were adhered to (Braun and Clarke, 2006; Creswell, 2007):

Transcription and Organisation of Data: Transcription involves the conversion of verbal and audio data into written text to aid further iterative reading and familiarisation (Braun and Clarke, 2006). Audio recordings from the eight interviews were transcribed verbatim for subsequent input into QSR NVIVO Software to aid analysis.

Iterative Reading and Data Coding: According to Braun and Clarke (2006), this stage involves detailed reading and grouping or categorisation of data for subsequent sorting into themes. Codes primarily refer to key or common words that reflect interviewees' intentions. When compared across all participant responses, it provides clarity to data and confirms consistency for drawing inferences (themes) (Creswell, 2007). This can be achieved manually or through the use of software depending on the volume of data (Saunders *et al.*, 2009).

Despite the relatively small respondent size of eight, QSR NVIVO software was used to provide a more detailed approach to coding and searching for patterns in the data. It was found necessary to aid easier analysis especially where further identification of themes was required (Ankrah, 2007). Common words and phrases on BIM qualification were also identified from the transcribed interview responses and cross-referenced to literature.

Establishment of Themes: Based on the coded responses, interviewee's opinions on BIM qualification criteria were further categorised into distinctive bur related concepts. Themes refer to distinctive patterns in qualitative data representative of salient or underlying concepts of the research (Thomas and Harden, 2008). According to Braun and Clarke (2006) this stage involves the establishment of distinctive concepts related to the research but requires judgement of the researcher. However, in order to mitigate the likelihood bias, researchers must rely on some cross-referencing to literature or prior formulation of ideas from theory (Creswell, 2007; Thomas and Harden, 2008).

The generated themes from the interviews were consistently reviewed to build a concise list reflective of the main purpose of the research. Some of the themes that emerged related to the importance of the BIM qualification process and relevant BIM qualification attributes. In relation to the identification of qualification criteria, the following additional guiding principles recommended for the identification of BIM capability criteria were followed in order to provide a holistic consideration of capability; practically meaningful and actionable; flexible and easy to adopt or adapt; measureable; neutral; informative; and consistent in their descriptions (Succar, 2009; Kam *et al.*, 2013).

Similar steps for qualitative data analysis were followed by Manu (2012) and Bashir (2013) in their study of accidents and lean factors in construction safety, respectively. The interview analysis aided the identification of multi-level hierarchies of assessment (decision) criteria supplier selection. This aided the semantic categorisation of BIM qualification criteria as well as identification of a preliminary order of importance for criteria. The relationships between the coding structure and emergent themes is presented and discussed.

6.3 INTERVIEW FINDINGS

Based on preliminary scoping of data and concurrence with BIM capability and CSC selection literature, four distinctive codes were generated for further analysis. These were *competence*, *capacity, culture and attitude* and lastly *cost.* These were subsequently categorised into themes for the main BIM qualification criteria. The qualification criteria themes were adopted for further categorisation of sub-criteria proposed by interviewees for BIM qualification of CSC for BIM projects. Interviewees were asked to list or suggest specific BIM qualification criteria they find important based on their experience or expert opinion. The suggested criteria were, thus, categorised based on the main qualification criteria themes. The rest of the interview results are presented in two sections, importance of qualification and proposed BIM qualification criteria.

6.3.1 The Importance of BIM Qualification in Pre-qualification and selection

According to Interviewees, BIM qualification is becoming an integral part of most construction projects in the UK especially large scale projects. Resultantly, most tender invitations and documentation now include a section on BIM qualification. Most clients and main contractors are more willing to work with a CSC that has BIM capability in addition to a willingness to learn. The interviews revealed that there is no specific approach to assessing CSC's ability to deliver BIM, though many firms are developing their own approaches to BIM qualification. While some interviewees had extensive knowledge about the assessment requirements stipulated in guidance documents (such as the PAS1192:2, 2013), most were of the opinion that they are not generally relied on for BIM qualification in practice. Interviewees also acknowledged that assessments are potentially complex in the CSC context because of the variety in types and sizes of organisations. The summary of responses is presented according to themes generated for classifying responses (Table 6.2.).

Table 6.2: Interviewees Opinion about the Importance of BIM Qualification

Themes	Remarks	Interviewee								Sample Quotes
		1	2	3	4	5	6	7	8	
Relevance of BIM Qualification *(i.e. during Selection or Pre-qualification)*	Interviewees highlighted the growing popularity of assessing BIM capability for the CSC before project commencement. It is becoming a key requirement for projects in UK especially clients eager to meet 2016 deadline.	×	×	×	×	×	×	×	×	*'We do fill PQQ forms on big jobs. What we realised is that there is now always a section in the PQQ [for BIM]'* (Interviewee 4). *'We just had a tender come back and the contractors had to say who their supply chain was and whether they are BIM capable……Currently most of these clients are concerned about the 2016 deadline approaching such as local authorities and a lot of them need to know whether the contractors are BIM capable'* (Interviewee 5).
Awareness, use and importance of BIM implementation guidance *(documents, standards and protocols)*	This theme highlighted the extent to which construction organisations rely on guidance documents, standards and protocols for BIM qualification. Including existing BIM capability frameworks and toolsets. It emerged that there is a lack of awareness or reliance on such documents by most organisations to aid BIM qualification.	×	×	×	×	×	×	×	×	*'The question about these protocols is that it is very important especially the PAS documents'* (Interviewee 4). *'after the PAS 1192 came out and until we adopted it we wouldn't have done any assessments'…..'there are a few frameworks but we don't find them very suitable, so we developed our own questionnaire but this was based on the CIPx forms'* (Interviewee 3). *'Do you find there is enough guidance from PAS and other documents like the CIC protocol on what you need to assess? Not really. I don't think so. Because with the level of detail it does become quite onerous and I think people have realised that'…the BIM maturity frameworks provide useful information but I don't think they are suitable to be used as PQQ's and the PAS91 contains very few broad BIM maturity questions which we would have assessed anyway'* (Interviewee 8). *'Do you find there is enough guidance from PAS and other documents like the CIC protocol on what you need to assess? Not really… I don't think so' … 'I know a few BIM capability frameworks but I honestly don't think anyone from industry uses them'* (Interviewee 7).
Need for BIM qualification criteria	This theme highlighted the need for tailored assessments to suit different contexts of CSC BIM usage.	×	×	×	×	×	×	×	×	*'if questions about equipment (BIM hardware) is asked to contractors you might not get the right responses as it would be to design team'* (Interviewee 7). *'for instance if you looking at concept design you will be creating questions around BIM carried out at concept design stage ….I guess and experience of creating BIM at that particular level'* (Interviewee 6). *'we do apply some weighting to criteria but some of the CIPx data may not be so important'* (Interviewee 3).

6.3.2 Proposed BIM Qualification Criteria

The main reason for this part of the study was to explore and generate a list of BIM qualification criteria based on interviewee's experience and knowledge. From the initial coding structure, eleven sub-themes were identified as the primary BIM qualification criteria for the CSC selection process. The relationship between the initial coding and generated themes is presented in Figure 6.1. This was relied on to subsequently map proposed criteria for BIM qualification as described in subsections.

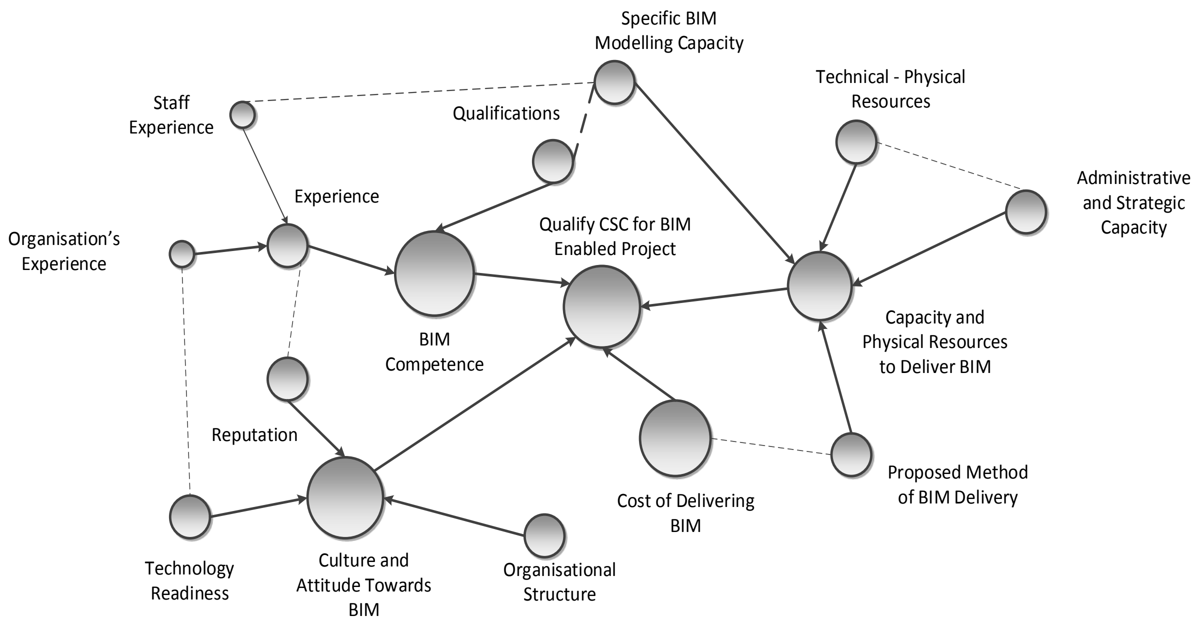


Figure 6.1: Thematic Map of BIM Qualification Criteria from Interview Data

6.3.2.1 Competence Related BIM Qualification Criteria

This theme was used to identify thematic areas which related to skills, experience and knowledge possessed by individuals or CSC in the delivery of BIM. The importance of these to BIM assessment was reiterated by all interviewees as reflected in the sample quote provided below.

"The roles, experience or qualifications of those people and then the IT competence generally are among the important things we need to consider when we are assessing our supply chain" [Interviewee 3].

The recurring sub-themes in the analysis of data within this category were *Professional and Academic Qualifications*, *Staff* and *Organisation's Experience* in the delivery of BIM. Out of the suggested BIM qualification criteria, 13 were categorised under these themes as presented in Table 6.3.

6.3.2.2 Qualification Criteria Related to BIM Capacity and Physical Resources

This theme is used to identify all criteria related to an internal capacity to deliver BIM. This included the specific ability to produce BIM deliverables through their physical, technical resources and expertise. The need for consideration of criteria related to this theme was noted by all interviewees as reflected in the sample quotes below.

"There is a need for questions assessing whether or not we have the relevant capabilities" [Interviewee 5] and "Y*ou want to know if they have the right data standards, machines* [hardware] *and software"* [Interviewee 7].

The themes identified in this category were: *Administrative and Strategic Capacity; Technical (Physical) Resources; Specific BIM Modelling Capacity* and *Proposed Methodology*. This category had the most number of suggested qualification criteria (22). A summary of the sub-themes and suggested criteria is presented in Table 6.4.

6.3.2.3 Identification of Culture and Attitude Related Qualification Criteria

In addition to the criteria related to experience, capacity and resources, interviewees further suggested criteria relating to the willingness and attitudes of organisations towards BIM. This can be inferred from the sample quote provided below.

"Especially culturally, that is actually, slightly different than having the capabilities, you might have the right capabilities but culturally you may not be willing to work with BIM" [Interviewee 2].

Table 6.3: Summary of Competence Related BIM Qualification Criteria from Interviews

		Description	Interviewee								Proposed Qualification Criteria
			1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	
Theme	Competence	**This theme is used to identify all criteria that relate to skills, experience and knowledge possessed by individuals or the CSC organisation to deliver BIM.** **Sample Quotes:** *'The first thing, we want to see on a project being tendered for is the BIM execution plan and roles and responsibility matrix'* (Interviewee 1). *'In summary, how many people? The roles, experience or qualifications of those people and then the IT competence generally' (Interviewee 3).* '*We need to ask how many, (BIM) beginners, intermediate and advanced users they have got within the firm….. or whether they can achieve those levels. But beyond that we don't really look at qualifications that much because we don't think it is the most important'* ….. *'Another thing we are looking at is the personnel they actually got'* (Interviewee 8).									
Sub-Theme	Professional and Academic Qualifications	Some criteria suggested related to availability of relevant professional and academic qualifications, certification and licenses held by CSC/tenderers as evidence of BIM knowledge and skills.	×	×	×			×		×	• Managerial Staff BIM Qualification • Key Technical Staff BIM Qualification • Staff Training or Continuous Professional Development • Qualified BIM Staff Availability for Project • Organisation's BIM Accreditations and Certifications • Organisation's BIM Training Arrangements
	Staff Experience	Some of the criteria mentioned by interviews relate to individual staff experience of working with BIM. Primarily skills and knowledge from historical / previous use or implementation of BIM	×	×	×	×	×	×	×	×	• Managerial Staff BIM Experience • Key Technical Staff BIM Experience
	Organisations Experience	Some other criteria mentioned by interviews relate broadly to the CSC's (tenderer) competence in relation to historical use or experience in BIM implementation and use.	×	×	×	×	×	×	×	×	• BIM Software Experience • Past BIM Project Experience • BIM Experience on Similar Project • Collaborative (Project) Procurement Experience • Internal Use of Collaborative IT Systems

Table 6.4: Summary of Capacity and Resources Related BIM Qualification Criteria

		Definition	Interviewee								Proposed Qualification Criteria
			1	2	3	4	5	6	7	8	
Theme	Capacity	**This theme is used to identify all criteria related to an internal capacity to deliver BIM. This included the specific ability to produce BIM deliverables through their physical, technical resources, expertise or processes.** **Sample Quotes:** '*There is a need for questions assessing whether or not we have the relevant capabilities'* (Interviewee 5). *'I think questions should be about how they plan to meet the EIR, Yes it is about the EIR…'* (Interviewee 6). '*Because you want to know if they can communicate with each other….. "You want to know if they have the right data standards, machines [hardware] and software" (Interviewee 7). Questions don't go into any depth and commit them to anything. So there has to be specific questions that are target the specifics rather than just asking what is your experience with BIM'* (Interviewee 7).									
Sub-Theme	Administrative and Strategic Capacity	Interviewees recommend the use of criteria that demonstrate maturity in internal processes in relation to vision, planning, development and management of resources for BIM implementation.	×	×	×	×		×	×	×	• IT Vision and Mission • BIM Vision and Mission • Quality of BIM Implementation Strategy • IT Expenditure (i.e. Budget) • IT Training Expenditure (i.e. Budget) • Level of Research and Development • Maturity in Change Management
	Technical (Physical) Resources	Some criteria related to the availability equipment and infrastructure related resources which will support the delivery of BIM.	×	×	×	×	×	×	×	×	• Hardware and State-of-the-art of Hardware • Software Availability • Data Storage (suitability and capacity) • Network Infrastructure Availability
	Specific BIM Modelling Capacity	This describes criteria that assesses expertise, internal procedures and processes specific to the creation of BIM models and data or working in common data environment.	×		×	×	×	×	×	×	• Internal Information Management Standards • BIM Standards • Data Classification and Naming Practices • Capacity - BIM Uses (Coverage from 2D to ND) • Capacity - BIM (Model) Maturity • Capacity - LOD/LOI • Model Server Usage
	Proposed Methodology	According to interviewees a key aspect of BIM qualification is the presentation of proposals specific to the tender invitation, work package or project BIM requirements (i.e. EIR and BEPs)	×	×	×	×		×	×	×	• Suitability -BIM Execution Plans for Project • Innovativeness in BIM Execution Plans for Project • BIM Vendor Involvement and Support to Firm • Suitability of Privacy and Security Plans for Project

The subthemes identified in this category were: *Technology Readiness (Attitude); Organisational Structure* and *Reputation* of organisation. Seven individual criteria were suggested after an analysis of interview comments. A summary of the themes and suggested criteria is presented in Table 6.5.

6.3.2.4 Cost as a BIM Qualification Criteria

Just as in many contractor selection models, the cost of delivery of BIM service is regarded as an important consideration by all the interviewees. Despite disagreements on the extent to which CSC organisations' must be allowed to charge extra fees for BIM, interviewees unanimously agreed that it is one of the most critical BIM qualification criteria. This is shown in the quote below.

"For a contractor they would generally put a cost on top to get a BIM manager which obviously will affect architect and M&E engineer's fees so obviously there is a cost from that end….. from QS point, It saves us time so the client will benefit from our fees being lower …at the moment and shows how competitive the market is because we are able to do a lot of things a lot quicker" [Interviewee 5].

This suggestion of cost/price being a key qualification criterion is consistent with general pre-qualification and selection practice (Hatush and Skitmore, 1997). There were no further sub-themes relating to this category. Cost or tender price was suggested as the main qualification criteria in this section. This is also presented in Table 6.5.

6.3.2.5 Evidence in BIM Qualification

In addition to the suggested criteria, interviewees suggested the following to be used as evidence or to aid effective assessment of CSC organisations: Filled CPIx forms such as the SCCS forms [PAS1192:2013] (Interview 3); tender PQQ (questionnaire) responses (Interviews 1,2,3,4,5,6,7 and 8); psychometric tests (Interviews 2,5,7 and 8); interviews with prospective CSC candidates; visits to CSC office or premises for physical inspections; (Interviews 3, 5,6,7 and 8); CV's of proposed personnel (Interviews 1,2,3,4,5,6,7 and 8); and testimonials and samples of BIM models or data previously generated (Interviews ,3,4,5,6 and 8).

Table 6.5: Summary of Culture, Attitude and Cost Related BIM Qualification Criteria

		Definition	**Interviewee**								**Proposed Qualification Criteria**
			1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	
Theme	Culture and Attitude	**This theme is used to identify all criteria related to organisation's culture or attitude towards BIM. These include soft measures related to the motivation to deliver BIM as well as collaborative ethos.** **Sample Quotes:** '*We just had a tender come back and the contractors had to say who their supply chain was and whether they are BIM capable ….. and if they are willing to get involved'* (Interviewee 1). *'To check attitude I think you need to have background information about the tenderer which you can build on and say this is my experience or maybe what you could find out about them…….if they have delivered in BIM environment to another client that we check online or contact this client for a reference'* (Interviewee 1). '*Especially culturally that is actually slightly different than having the capabilities, you might have the right capabilities but culturally you may not be willing to'* (Interviewee 2). '*We are interrogating their willingness to do BIM more than before'* (Interviewee 8).									
Sub -Theme	Technology Readiness	This describes criteria that assesses attitudes towards technological innovation such as BIM	×	×	×		×	×		×	• Attitude and Willingness • Youthfulness of Staff • Graduates in Firm • Awareness of BIM Benefits • Extent of IT Support to Existing Ways of Working in Organisation
	Organisational Structure	Indicators or evidence of appropriate collaborative culture within firm and whether the organisational makeup of the CSC organisation can support innovation and common data environments such as BIM	×							×	• Suitable Organisational Structure for Collaboration (Evidence of Decentralisation)
	Reputation	This describes any indicators of satisfaction with previous approach to working with BIM	×	×			×			×	• Performance on Past BIM projects (Satisfaction) • Relationship with Principle Supplier (Satisfaction)
Theme	Cost	The cost of BIM service being offered '*The price being charged is very important in selection'…'For a contractor they would generally put a cost on top to get a BIM manager'* (Interviewee 5).									
Sub -Theme	Price Charged to Deliver BIM Service	The cost of the BIM service was viewed by interviewees as one of the most important considerations for assessment	×	×	×	×	×	×	×	×	• Tender Price/Cost of BIM Service

The suggested evidence or approaches to effective assessment were certification held by individual staff or the organisation itself. According to Interviewee (8), certification schemes such as the Building Research Establishment's (BRE) certification scheme are becoming important in the BIM qualification process. Another scheme mentioned was Autodesk certification for individual Revit users. Though some interviewees were worried about the authenticity of certifications that some CSC firms currently show as demonstration of their competence, they were of the opinion that schemes such as BRE certification and University Degrees in BIM were gradually becoming prevalent.

One of the interviewees [Interviewee 3] had extensively relied on the CIC (2013) and PAS1192:2013 (2013) to aid the development of pre-qualification questionnaires. Most of the interviewees had, however, relied on ad-hoc approaches as well as personal experience and judgement. There was clearly no reliance on some of the BIM capability frameworks and tools reviewed in *Section 3.3* of this study. The CIC (2012) planning guide for owners was however relatively known by some of the interviewees who, however, only refer to it generally for BIM implementation guidance rather than for qualification.

6.3.3 Comparison of Proposed BIM Qualification Criteria with Existing Frameworks

Albeit a few omissions, suggested criteria were largely similar to criteria relied on in five of the most relevant BIM capability frameworks to pre-qualification and selection as shown in Table 6.6 and 6.7.

While *Hardware* was suggested as a criterion, one interviewee recommended the need to assess how modern the hardware systems are within an organisation. This is shown in the extracted interview quote below.

'Before you're selected to deliver BIM, you need to have the most up-to-date systems…we have been on projects where some consultant's machines just couldn't cope with some versions of files from other consultants..… (Revit files and other software files) ….' [Interviewee 7].

Table 6.6: Comparison of Proposed Qualification Criteria with Relevant Frameworks (Part 1)

BIM Qualification Criteria			Interviews	Quickscan TNO	VDC Scorecard	BIMMI (Succar)	CIC (2012)	Giel and Issa (2014)
Competence	Qualification	Managerial Staff BIM Qualification	X	O	X	O	O	O
		Key Technical Staff BIM Qualification	X	O	X	X	O	O
		Staff Training and CPD	X	O	X	X	X	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
		Collaborative (Project) Procurement Experience	X	O	0	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
		BIM Vision and Mission	X	X	X	X	X	X
		Quality of BIM Implementation Strategy	X	X	X	X	X	X
		Change Management Maturity	X	X	X	X	X	X
		IT Budget	X	X	X	O	-	O
		IT Related Training Budget	X	O	O	-	-	O
		BIM Research and Development	X	x	X	x	O	X

(×) largely considered, **(o)** - somewhat considered, **(-)** not considered

[The reviewed frameworks are the most relevant to pre-qualification and selection: Quickscan (van Berlo *et al.,* 2012); VDC (Kam *et al.,* 2014); BIMMI (Succar, 2010); CIC (CIC, 2013b); and (Giel and Issa, 2014)]

Table 6.7: Comparison of Proposed Qualification Criteria with Relevant Frameworks (Part 2)

BIM Qualification Criteria			**Interviews**	**Quickscan TNO**	**VDC Scorecard**	**BIMMI (Succar)**	**CIC (2012)**	**Giel and Issa (2014)**
Capacity and Resources	Technical (Physical) Resources	Hardware	X	X	X	X	X	X
		Hardware: State-of-the-art	O	O	O	X	O	O
		Software Availability	X	X	x	X	X	X
		Data Storage Capacity	X	X	x	O	O	X
		Network Infrastructure Availability	X	X	X	X	O	X
	Specific BIM Modelling Capacity	Internal Information Management Standards	X	X	X	X	X	O
		BIM Standards	X	X	X	X	X	X
		Data Classification and Naming Practices	X	X	X	O	X	X
		BIM Coverage (Uses) Capacity	X	X	X	X	X	X
		BIM Model Maturity Capacity	X	X	X	X	X	X
		LOD/LOI Capacity	X	X	X	O	X	X
		Model Server Usage	X	X	O	O	O	O
	Proposed Methodology	Suitability of Proposed BIM Execution Plans for Project	X	-	X	O	X	O
		Innovativeness in Proposed BIM Execution Plans for Project	X	-	O	-	X	0
		BIM Vendor Involvement and Support	X	O	O	O	O	-
		Suitability of Privacy and Security Plans	X	O	X	X	O	O
Culture and Attitude	Reputation	Relationship with Principle Supplier(Satisfaction)	X	-	O	-	-	-
		Performance on Past BIM projects (Satisfaction)	X	-	O	-	O	-
	Technology Readiness	Attitude Towards New Technology/Willingness	X	X	X	O	X	X
		Youthfulness of Staff	O	-	-	-	-	-
		Graduates in Firm	O	-	-	-	-	-
		Awareness of BIM Benefits (in project context)	X	-	O	O	X	O
		Extent of IT Support to Core Business/Processes within Firm	X	O	X	O	O	O
	Organisational Structure	Organisational Structure – Level of Decentralisation	X	X	X	X	X	O
Cost	Cost	Cost/Price of BIM Service	X	-	-	-	X	-

(×) largely considered, **(o)** - somewhat considered, **(-)** not considered

[The reviewed frameworks are the most relevant to pre-qualification and selection: Quickscan (van Berlo *et al.,* 2012); VDC (Kam *et al.,* 2014); BIMMI (Succar, 2010); CIC (CIC, 2013b); and (Giel and Issa, 2014)]

Based on this assertion, State-of-the-art of Hardware was added having been previously considered in BIM capability frameworks (Succar, 2010; Hanafizadeh and Ravasan, 2011; van Berlo et al., 2012). The other two criteria deduced from thematic analysis of interviews were youthfulness of staff and graduates in firm. Though these were not directly proposed by interviewees it can be inferred from the following quotes.

'….I believe younger people who have recently graduated are more interested in BIM, even most of our interns like to be involved……the older guys don't even really know what BIM is….I believe when you are working with consultants with younger and tech savvy staff you are most likely to achieve results with BIM '[Interviewee 3]. '*….one of the problems in industry is resistance to change….. some of the older consultants are surprisingly not there yet with BIM* …'[Interviewee 5].

'Youthfulness of staff' and 'number of graduates' in a firm were previously used as criteria for assessing IT readiness in organisations (Hanafizadeh and Ravasan, 2011), thus, included in the proposed list of criteria for this study.

6.4 SUMMARY OF INTERVIEW FINDINGS

Out of four categories of BIM qualification assessment, eleven distinctive qualification criteria were deduced from the interview data. The categories were: competence referencing 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 were also suggested as a category for soft qualification criteria that indicate the appropriate culture and willingness to deliver BIM; and finally the cost of delivery BIM. The eleven main BIM qualification criteria deduced from the interview themes were: *Qualification, Staff Experience, Organisation Experience, Administrative and Strategic Capacity, Technical (Physical) Resources, Specific BIM Modelling Capacity, Proposed Methodology, Reputation, Technology Readiness, Organisational Structure, and Cost.* A total of 45 sub-criteria were proposed across the eleven main BIM qualification criteria as presented in Tables 6.6 and 6.7.

6.5 CHAPTER SUMMARY

In this chapter the procedure for the qualitative phase of this study has been explained together with a discussion of the approach to analysis. Results from the analysis of interview data from eight construction industry experts in BIM implementation are also presented. A proposed list of 45 criteria is subsequently proposed as part of eleven main BIM qualification criteria. In order to establish which of the criteria are most relevant and whether there are omissions, a Delphi study with a wider group of construction industry practitioners was conducted. The procedure and results of this second phase of the study is presented in the next chapter.

CHAPTER 7: ANALYSIS AND RESULTS OF THE QUANTITATIVE ENQUIRY

7.1 INTRODUCTION

In the previous chapter, the findings of the qualitative enquiry is presented. These findings are further tested in a quantitative enquiry as part of the second phase of the research design. According to Fellows and Liu (2008), quantitative research is used when there is a need to test objective theories or prior formulations through the examination of relationships among variables. It usually involves the numerical and objective measurement of variables (Creswell, 2003). Thus, quantitative studies involve asking questions relating to what, how much and how many. In this study the quantitative phase is used to identify the critical criteria among the 45 proposed BIM qualification criteria arising out of the qualitative enquiry. Furthermore, the contribution of BIM qualification criteria to BIM delivery success, in the CSC context is assessed. The quantitative phase of this study consists of two parts: a *Delphi* study of experienced practitioners and a general survey of practitioners on BIM-enabled projects in UK. The results of the quantitative phase are presented in this chapter. This chapter also includes a review of the data analysis techniques and justification for the chosen methods.

The quantitative phase of this study was executed as follows:

- Development of survey instrument (Delphi and general survey respectively);
- Testing and revision of the survey instrument;
- Identification of participants (Delphi) and sampling (general survey);
- Distribution of the survey instrument (questionnaires); and
- Analysis of the survey data.

7.2 DATA ANALYSIS - THE QUATITATIVE ENQUIRY

A wide range of quantitative data analysis techniques were employed to assess survey respondents' opinions on critical BIM qualification criteria as well as their perceived contribution towards delivery success within the CSC as shown in Table 7.1.

Table 7.1: Data Analysis Techniques for Quantitative Enquiry

	Quantitative Data Analysis Technique	Objective	Contribution to Research Objectives
Part 1	**Delphi Survey**	**Generate a concise list of the most critical BIM qualification criteria**	**Objective 3:** Identify the ***most critical criteria*** and prioritise them based on their relative contribution to the successful delivery of BIM
	Descriptive (Means, Standard Deviation, Frequencies)	Interpretation and feedback	
	Relative Importance Index (RII)	Ranking of critical BIM qualification criteria	
	R-Inter-rater Agreement (r_{wg}):	Test of consensus among participants	
	Spearman's rho	Test of stability between Delphi rounds	
Part 2	**General Survey**	**Model relationships between BIM qualification criteria and delivery success. Ascertain weighted contribution of BIM qualification criteria to delivery success.**	**Objective 3:** Identify the most critical criteria and prioritise them based on their ***relative contribution to the successful delivery of BIM.*** **Objective 4:** Ascertain the impact of qualification criteria on specific BIM delivery success areas in the Supply Chain Context of BIM use
	Descriptive (Means, Standard Deviation, Frequencies)	General description of data and pattern identification	
	Relative Importance Index (RII)	Ranking of critical (BIM qualification criteria) contributors to delivery success	
	Spearman's rho	Test of relationship between criteria importance and relative contribution to delivery success	
	Pearson's Product-moment Coefficient	Test of association between variables (i.e. BIM qualification criteria and various elements of delivery success)	
	Multiple Regression Analysis	Predict and model influence of BIM qualification criteria on delivery success [including influence of project/organisational complexity characteristics]	
	Analysis of variance (ANOVA)	Assess effect of organisational characteristics on delivery of success	

7.3 THE DELPHI SURVEY (Quantitative - Part 1)

As stated in Table 7.1, the Delphi survey was used to identify the most critical among the BIM qualification criteria proposed from the interviews. The three critical parts of the Delphi procedure, are the selection of participants, the determination of consensus and the termination of iterative rounds of survey. The Delphi procedure for this study is outlined below.

7.3.1 Delphi Participant Selection

Delbecq *et al.* (1975) recommends that researchers use a minimum, but sufficient number of participants in view of the iterative nature of survey administration. According to Linstone and Turoff (1975), the number of participants should not be considered as important as much as the knowledge possessed by participants on the subject. Hallowell and Gambatese (2010) similarly noted that contextual characteristics of the research (namely, the number of available experts, the desired geographic representation and the capability of the facilitator) should be the main considerations for sample size determination. Delbecq *et al.* (1975) suggested ten to fifteen (15) participants. A review of Delphi usage within construction reveals the use of between 3 to 46 participants with an average of 16 experts per study (Table 5.2). Based on these research findings, it was ensured that the sample size of the Delphi study exceeded 16 participants to ensure it conformed to common practice in the construction management field.

The contact list generated for the first phase of the research was also employed for the Delphi study. Purposive identification of Delphi participants is widely used since the primary objective of Delphi is the selection of respondents' deemed to be knowledgeable in the research subject (Hallowell and Gambatese, 2010). This resulted in the extension of invitations to 60 practitioners who met the selection criteria for the Delphi survey (S*ection 7.3.2*).

Out of the 60 practitioners contacted, 35 responses were received out of which 30 were valid representing a 50% response rate. The responses were scrutinised from the initial 35, resulting in the elimination of five questionnaires due to missing data. After the first round, descriptive statistics (including means) were computed and a summary provided to participants as part of feedback and also in order to meet the methodological requirements of Delphi studies. The first round responses were sent to participants together with another set of questionnaires. The second round resulted in 25 responses representing an 83.3% retention rate between the Delphi rounds. The response rate is presented in Table 7.2.

Table 7.2: Delphi Survey Response and Retention Rate

	Round 1	**Round 2**
Experts Contacted /Invited	60	30
Valid Returned Questionnaires	30	25
Percentage Response (%)	50.0%	83.3%

7.3.2 Delphi Participant Backgrounds

Choosing appropriate subjects is one of the most important steps in the Delphi process as this ensures quality and validity (Okoli and Pawlowski, 2004). Since the Delphi technique focuses on eliciting expert opinions, the criteria relied on must ensure the selection of the most knowledgeable and experienced people in the subject area. The Delphi panel may also consist of individuals who are primary stakeholders or have considerable interest in the subject (Hsu and Standford 2007). As a result, criteria should include competencies relating to the qualification, position and professional experience of the prospective Delphi participants (Gupta and Clarke, 1996). Where academics are included, this may include a need for a requirement of their authorship or publication of research in the subject area (Sourani and Sohail, 2014). Other factors include the willingness of subjects to be part of the Delphi process. In addition, best practice requires that a set of qualifying criteria is used to pre-qualify a list of possible subjects, who can then be officially invited, with a clear delineation of the requirements for participation (Rowe and Wright, 1999).

The following criteria were the basic benchmarks for participation in this study: at least five years construction experience, at least two years BIM experience, participant in the pre-qualification or selection process for CSC on a BIM project or author of a published BIM and CSC academic peer reviewed paper. Expertise was considered broadly in relation to Virtual Digital Construction (VDC) rather than just BIM. A lesser number of years BIM (or VDC) experience was considered acceptable in view of the relative novelty of BIM within UK construction. With respect to novelty, it is worth noting that, the promotion of universal adoption of BIM started in the UK in 2011 (BIS, 2011), hence, at the point of data collection (2014), two years' experience was deemed appropriate for the UK context. Nonetheless, most participants had significant and extensive BIM or VDC experience preceding UK BIM implementation. This is detailed in the next sub-section.

7.3.2.1 *Background of Respondents to the Delphi Survey*

The majority of respondents were Architects (26.7%) followed by Quantity Surveyors (20%) then Project and Construction Mangers (16.7%). The job description of respondents included Architect (13.3%), BIM Manager (10%), Design Manager (6.7%) and Senior Quantity Surveyor (6.7%). In addition to industry practitioners, there were also several academic contributors to the Delphi study. This included BIM researcher (10%) and Senior Lecturer (10%) in construction collaborative technologies and BIM. Majority of all respondents held at least a Masters degree (46.7%) with a significant proportion (23.3%) holding a Doctorate degree. This is summarised in Table 7.3.

Table 7.3: Background of Delphi Respondents

		Frequency	%
Profession	Project / Construction Manager	5	16.7
	Architect	8	26.7
	Quantity Surveyor	6	20.0
	Engineer	3	10.0
	Academic Lecturer	4	13.3
	Academic Researcher	4	13.3
Job Description/Role	Architect	4	13.3
	BIM Manager	3	10.0
	Building Design Manager	1	3.3
	Building Services Advisor	1	3.3
	Construction Manager	1	3.3
	Contractor	1	3.3
	Design Consultant	1	3.3
	Design Coordinator	1	3.3
	Design Manager	2	6.7
	Director	1	3.3
	Managing Quantity Surveyor	1	3.3
	Professor	1	3.3
	Project Architect	1	3.3
	Quantity Surveyor	1	3.3
	Research Associate	1	3.3
	Researcher-BIM	3	10.0
	Senior Commercial Manager	1	3.3
	Senior Lecturer	3	10.0
	Senior Quantity Surveyor	2	6.7
Qualification	HND	3	10.0
	Bachelor's Degree	5	16.7
	Master's Degree	14	46.7
	Doctorate Degree	7	23.3
	Other	1	3.3

From Table 7.4, it is evident that the Delphi participants in this study were sufficiently experienced both within the construction industry as well as in the delivery of BIM and other VDC technologies. Respondents possessed an average of 16 years industry experience with some participants having as high as 40 years construction industry experience. Respondents could demonstrate an average of 7 years in BIM or VDC and an average of 10 years involvement in tender, pre-qualification or selection activities. The background of participants is indicative of the fact that the respondents were knowledgeable and experienced in the research subject area due to their professional roles and experience.

Table 7.4: Delphi Participants' Experience

Experience	Years of Experience		
	Lowest	Highest	Average
Construction Industry	5	40	16
Usage of BIM / Virtual Digital Construction Technology	2	25	7
Tendering, Prequalification and Selection	1	25	10

7.3.2.2 Design of the Delphi Survey Questionnaire

A simple questionnaire was designed in order for participants to rate the extent to which they agree that the proposed criteria from the interviews were critical to BIM qualification of the CSC (Appendix C). Respondents were asked to provide a rating for each of the 45 sub-criteria constituting the third level of the proposed BIM qualification criteria hierarchy. The questionnaire requested participants to state the extent of their agreement with the use of the proposed criteria in determining suitable CSC candidates on BIM-enabled projects. This was achieved with the aid of a 5-point Likert-scale response with the following linguistic scales: *Strongly Disagree, Disagree, Neither Agree or Disagree, Agree, and Strongly Agree*. Likert-scales are the most widely used to support statistical test of consensus in Delphi studies (von der Gracht, 2012).

Respondents were encouraged to provide preferential rating of criteria where more than one criterion was deemed to measure the same effect. This was to ensure that the critical criteria identified were representative, concise and complete. The questionnaire consisted of open ended questions which allowed participants to discuss the proposed criteria as well as recommend additional criteria. No new criteria were, however, proposed at the end of Delphi survey. Furthermore, the questionnaire requested information about participants' background and years of experience in construction, BIM and VDC, as well as CSC procurement as outlined above.

7.3.3 Statistical Techniques for Delphi Data Analysis

The statistical techniques used for the Delphi data analysis is detailed below.

7.3.3.1 Descriptive Statistics

Descriptive statistics are often used to uncover the patterns, distributions and peculiarities within a data sample (Denscombe, 2010). The Delphi data consisted mainly of a univariate type of data, thus, frequency distributions were deemed as appropriate to ascertain the distribution of data (Naoum, 2007). Measures of central tendency were used to identify mean response points with respect to the Likert-scales (Denscombe, 2010). Other measures of central tendency, such as median and mode, do not take into account outliers, and thus, were not used at this stage. Standard Deviation (SD) was, however, deployed to assess the extent of spread in responses.

7.3.3.2 Relative Importance Index (RII)

Another descriptive statistic used was the Relative Importance Index (RII). This was used to convert frequencies on each ordinal data point into an aggregated index of scores to aid ranking of criteria. This ranking aided both prioritisation and subsequent correlation analysis. RII is widely used for generating ranking among variables with cognisance of the relative contribution of frequencies on each scale point of measurement. It has been previously used by Babatunde *et al*. (2010) and Bashir (2013) for prioritising procurement selection factors and lean factors in construction safety, respectively. The formula for RII is presented in Equation 7.1 (Babatunde *et al.*, 2010).

These descriptive statistics are not often used for detailed or inferential analysis but form basis for an understanding of the data, as well as aiding further and more robust analyses of inter-rater agreement.

Equation 7.1: Relative Importance Index (RII)

$$RII = \sum_{1}^{5} \frac{(N_i \times K_i)}{(R_h \times n)}$$

Where:

N_i = the number of respondents choosing rating point *ki, i*=(1≤,*i*,≥5);

K_i = rating points (1 to 5) on Likert-scale;

n = the total number of responses for variable; and

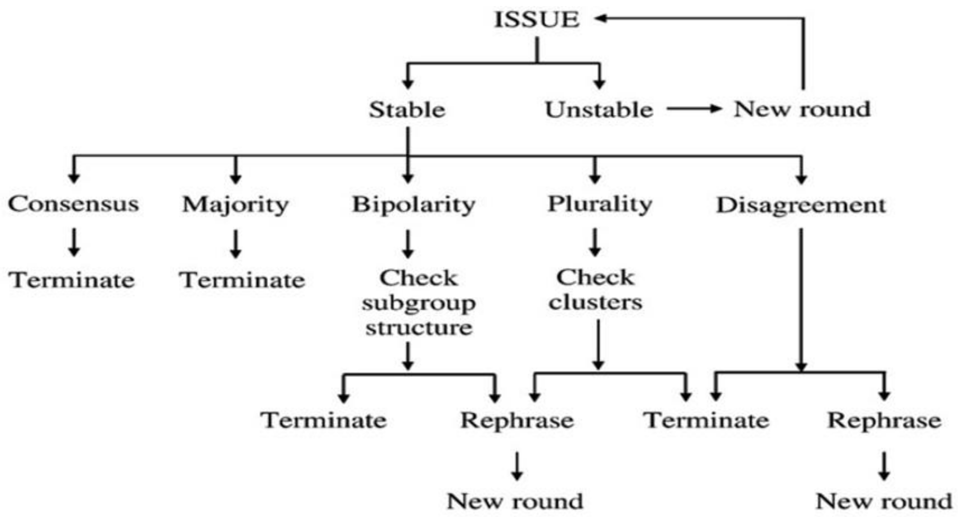
R_h = the highest value in ranking order.

7.3.4 Determination of Delphi Stability and Consensus

A typical Delphi process involves rounds of data collection and feedback for preliminary analysis after each round (von der Gracht, 2012). Consensus in Delphi represents a point at which the iteration is terminated. This makes the determination of consensus and termination of Delphi rounds the most critical aspects of the procedure. In order to meet this principal requirement of Delphi, it was consequently necessary to use appropriate statistical methods for the determination of consensus among participants.

Delphi traditionally consists of three rounds, namely, brainstorming, narrowing down and final ranking of factors. The number of rounds may, however, continue until consensus is reached (von der Gracht, 2012). The brainstorming round leads to more effective data instrument development (Hallowell and Gambatese, 2010; von der Gracht, 2012). In this study, the qualitative enquiry provided relevant data which would normally be collected during the brainstorming phase, in a typical Delphi process. Regardless of the point of commencement of Delphi rounds, however, there must be a methodical approach to determining consensus and thereby terminating the process (Delbecq *et al.,* 1975).

Others have separated the concepts of consensus and termination with the introduction of the concept of stability representing the consistency of responses between successive rounds of a Delphi survey (von der Gracht, 2012). Thus, the attainment of consensus or consistency are indicators for the termination of Delphi rounds. Theoretical and practical factors also need to be included in the decision to terminate the rounds in the Delphi process (Dajani, 1979) as shown in Figure 7.1.



Source: *Dajani (1979) reused with permission from © Elsevier*

Figure 7.1: Termination of Rounds in Delphi

Many methods of consensus or stability measurement have evolved as a result of the proliferation of Delphi as a research technique. Von der Gracht (2012) identified three main approaches to measure consensus and stability. These were subjective determination by researcher, the use of descriptive statistics and the use of inferential statistical measurement of agreement and consistency. In this study, statistical measures of agreement were adopted to measure both consensus and stability.

7.3.4.1 Determination of Consensus - Inter-rater Agreement (r_{wg})

The r_{wg} was considered as the most appropriate to ensure confidence in interpreting the results based on a review of previous Construction Management studies (Manu, 2012; Bashir, 2013). It was deemed appropriate given that most adopted measures towards the determination of consensus in Delphi with respect to construction research, has either been descriptive or qualitative. It was concluded that the adoption of a more robust computational approach to determination of inter-rater agreement would provide more confidence in the measurement of consensus. This was achieved with the use of the '*R'* statistical software of inter-rater agreement (r_{wg}).

James *et al*. (1984) proposed a single item inter-rater agreement index (r_{wg}) and a multiple-item scale inter-rater agreement index ($r_{wg(j)}$) to measure agreement in single-item and multiple-item situations. This test allows the evaluation of the extent to which raters' tend to make similar judgements in their expression of an opinion (Tinsley and Weiss 1975). It provides a statistically significant measure of the consistency of agreement among raters (Mandrekar, 2011). According to James *et al.* (1984), the single item inter-rater agreement index (r_{wg}) is a reliable indicator of consensus and homogeneity in judgements within groups. According to Manu (2012) the r_{wg} statistic remains popular as a result of associated techniques that can be applied to improve the statistical reliability of outputs (Schmidt and Hunter, 1989; Kozlowski and Hattrup, 1992; Cohen *et al.*, 2001; Harvey and Hollander, 2004).

Statistical Significance of Inter-rater test results: Despite a conventional acceptance of r_{wg} values equal to or greater than 0.7 as adequate indication of consensus, it is also acknowledged that sample size and number of variables affect reliability of scores (Harvey and Hollander, 2004). According to Cohen *et al*. (2001), the r_{wg} index values of 0.7 may, therefore, not be adequate in showing agreement in some circumstances. A method for the determination of a minimum acceptable r_{wg} has therefore been proposed and incorporated within the '*R'* software package. In this study, a reliability test consisting of 10,000 simulation runs was relied on to ascertain minimum acceptable r_{wg} value (Bliese 2000). The minimum threshold of agreement was found to be $r_{wg} = 0.75$, specifically based on the characteristics of the data collected for this study. From this analysis, only criteria with $r_{wg} \geq 0.75$ were therefore considered as reaching consensus. The mean scores of all criteria achieving $r_{wg} \geq 0.75$ were then examined further to identify the most critical criteria.

7.3.4.2 Stability Between Delphi Rounds - Spearman's rank correlation coefficient

Spearman's coefficient normally denoted by *rho* or ρ is a non-parametric test for statistical dependence between two variables (Jamieson, 2004). It compares the medians of these variables, thus, making it a preferred option for correlation analysis of ordinal data (Field, 2000). Considering the ordinal nature of the data gathered from the questionnaires, this test was applied to assess the extent to which the opinions of Delphi experts changed between the rounds. It is advocated that tests are run to ascertain whether or not significant differences exist between expert ratings of variables and in between rounds as a measure of stability. The Delphi process can then be terminated once there is no significant difference in expert opinion between subsequent rounds (Delbecq *et al.,* 1975). The Spearman rank correlation coefficient is expressed as follows (Equation 7.2).

Equation 7.2: Spearman's Correlation Coefficient

$$\rho = 1 - \frac{6\sum d_i^2}{n(n^2 - 1)}$$

Where:

d_i = the difference in the ranks given to the two variables; and

n = the number of pairs of ranks.

The correlation coefficient represents the measure of relationship between the rank order of variables which occur between the Delphi rounds. This correlation coefficient varies between +1 and -1, with the closer values to +1 representing a perfect positive correlation while the closer to -1 represents negative relationships. In this study, the Delphi survey was terminated after the second round as a result of positive (near +1) *rho* values following a test of correlation.

7.3.5 Delphi Results – Identification of Critical BIM Qualification Criteria

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 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 or Disagree, 4 = Agree, 5 = Strongly Agree*). From the principles of mathematical approximation, BIM qualification criteria with mean values ≥ 3.5 were accepted as critical provided there was consensus among participants ($r_{wg} \geq 0.750$). This was to ensure that the rules of Delphi were met as well as guaranteeing that the mean rating was statistically acceptable to most participants in the Delphi survey.

7.3.5.1 Most Critical Competence Related Qualification Criteria

The test of stability was achieved by the second round for all variables in this category [*rho* = 0.857, $p < 0.01$], indicative of significant and high degree of correlation, hence, stability. All variables in this segment did not, therefore, need further testing in a subsequent round of Delphi. The results from the second round of the survey were then run through the consensus test to identify the most critical qualification criteria. From the tests of consensus, three of the proposed sub-criteria were eliminated, namely, *Managerial Staff BIM Qualification* (Mean = 3.560 and r_{wg} = 0.705), *Staff Training and CPD* (Mean = 4.040 and r_{wg} = 0.730) and *Collaborative Procurement Experience* (Mean = 4.000 and r_{wg} = 0.708). Despite recording acceptable mean scores, all of the above criteria failed the inter-rater agreement test, indicating lack of consensus across the entire group of Delphi participants. This is indicative of disagreement among significant number of respondents. This is also indicative of perceptions of similarity of the criteria in terms of what they purport to measure. Most other sub-criteria in this segment were, however, retained. Furthermore, all main criteria retained more than one of their constituent sub-criteria. All main BIM qualification criteria suggested in the category were, therefore, retained. The results are summarised and presented in Table 7.5. The summary of results includes the rating of criteria importance in both Delphi rounds one and two.

Table 7.5: Determination of Critical Competence Related BIM Qualification Criteria

BIM Qualification Criteria		Delphi Round 1				Delphi Round 2				Agreement and Consensus Summary			
		N	Mean	S.D	RII	N	Mean	S.D	RII	r_{wg}	r_{wg} ≥0.75	Mean ≥.3.5	Remarks
Qualification	Managerial Staff BIM Qualification	30	3.533	0.937	0.710	25	3.560	0.768	0.710	0.705	No	Yes	Removed
	Key Technical Staff BIM Qualification	30	3.967	1.066	0.790	25	4.200	0.646	0.840	0.792	Yes	Yes	√
	Staff Training and CPD	30	3.967	0.850	0.790	25	4.040	0.735	0.810	0.730	No	Yes	Removed
	BIM Staff Availability for Project	30	4.567	0.626	0.910	25	4.680	0.627	0.940	0.803	Yes	Yes	√
	Organisation's BIM Accreditations and Certifications	30	3.767	0.774	0.750	25	3.840	0.625	0.770	0.805	Yes	Yes	√
	Organisation's BIM Training Arrangements	30	3.933	0.740	0.790	25	4.000	0.707	0.800	0.750	Yes	Yes	√
Staff Experience	Managerial Staff BIM Experience	30	4.000	0.643	0.800	25	3.960	0.455	0.790	0.897	Yes	Yes	√
	Key Technical Staff BIM Experience	30	4.200	0.805	0.840	25	4.200	0.646	0.840	0.792	Yes	Yes	√
Organisation Experience	BIM Software Experience	30	4.500	0.630	0.900	25	4.640	0.569	0.930	0.839	Yes	Yes	√
	Past BIM Project Experience	30	4.100	0.885	0.820	25	4.200	0.577	0.840	0.833	Yes	Yes	√
	BIM Experience on Similar Project	30	4.000	0.947	0.800	25	4.240	0.597	0.850	0.822	Yes	Yes	√
	Collaborative (Project) Procurement Experience	30	3.933	0.868	0.790	25	4.000	0.764	0.800	0.708	No	Yes	Removed
	Internal Use of Collaborative IT Systems	30	3.867	0.776	0.770	25	3.960	0.539	0.790	0.855	Yes	Yes	√
Stability Between Round 1 and 2 Spearman's rho [0.857** $p < 0.01$] ** Correlation is significant at the 0.01 level (2-tailed) Acceptable agreement between rounds hence terminated at Round 2													

√ = Represents retained (critical) BIM qualification criteria

The critical BIM qualification sub-criteria in the competence category were: *Key Technical Staff BIM Qualification; BIM Staff Availability for Project; Organisation's BIM Accreditations and Certifications; Organisation's BIM Training Arrangements; Managerial Staff BIM Experience; Key Technical Staff BIM Experience; BIM Software Experience; Past BIM Project Experience; BIM Experience on Similar Project;* and *Internal Use of Collaborative IT Systems.*

7.3.5.2 Critical Capacity and Resources Related Qualification Criteria

The test of stability between the rounds yielded a highly positive Spearman's rho [$rho = 0.964$, $p < 0.01$], indicative of a significant and very high degree of correlation (stability). All variables in this segment did not, therefore, need further tests of agreement after the second Delphi round.

The results from the second round of the Delphi survey were then given the test of consensus (agreement) in order to identify critical criteria. From the tests of consensus, eleven out of the 23 proposed qualification sub-criteria were eliminated. The eliminated sub-criteria included *BIM Vision and Mission* (Mean = 4.480 and r_{wg} = 0.703) which was eliminated in favour of *IT Mission and Vision.* Others included *Change Management Maturity* (Mean = 3.520 and r_{wg} = 0.650), *IT Budget* (Mean = 3.040 and r_{wg} = 0.772) and *IT Related Training Budget* (Mean = 3.600 and r_{wg} = 0.667). Neither of the criteria for assessing hardware capabilities passed the consensus test. *Hardware* (Mean = 3.920 and r_{wg} = 0.711) and *Hardware-State-of-the-art* (Mean = 3.160 and r_{wg} = 0.763) were not deemed as critical to BIM qualification of the CSC. The remaining criteria eliminated were *Internal Information Management Standards* usage (Mean = 4.360 and r_{wg} = 0.630), *BIM Coverage (uses) Capacity* (Mean = 3.480 and r_{wg} = 0.620), *Model Server Usage* (Mean = 3.240 and r_{wg} = 0.697), *Innovativeness in BIM Execution Plans (BEP)* (Mean = 3.440 and r_{wg} = 0.747) and *Suitability of Privacy and Security Plans* (Mean = 3.960 and r_{wg} = 0.730). All the main BIM qualification criteria retained more than one of its constituent sub-criteria as presented in Table 7.6.

Table 7.6: Determination of Critical Capacity and Resources Related Criteria

BIM Qualification Criteria		Delphi Round 1				Delphi Round 2				Agreement and Consensus Summary			
		N	Mean	Std. D	RII	N	Mean	Std. D	RII	Rwg	Consensus	Mean ≥3.5	Retained
Administrative and Strategic Capacity	IT Vision and Mission	30	3.733	0.828	0.747	25	3.840	0.688	0.768	0.763	Yes	Yes	√
	BIM Vision and Mission	30	4.500	0.630	0.900	25	4.480	0.770	0.900	0.703	No	Yes	Removed
	Quality of BIM Implementation Strategy	30	4.400	0.621	0.880	25	4.200	0.577	0.840	0.833	Yes	Yes	√
	Change Management Maturity	30	3.567	0.898	0.710	25	3.520	0.872	0.700	0.650	No	Yes	Removed
	IT Budget	30	3.267	0.907	0.650	25	3.040	0.676	0.610	0.772	Yes	No	Removed
	IT Related Training Budget	30	3.533	0.860	0.710	25	3.600	0.817	0.720	0.667	No	Yes	Removed
	BIM Research and Development	30	3.700	0.794	0.740	25	3.760	0.597	0.750	0.822	Yes	Yes	√
Technical (Physical) Resources	Hardware	30	3.933	0.868	0.790	25	3.920	0.759	0.780	0.711	No	Yes	Removed
	Hardware: State-of-the-art	30	3.433	0.898	0.690	25	3.160	0.688	0.630	0.763	Yes	No	Removed
	Software Availability	30	4.167	0.791	0.830	25	4.160	0.554	0.830	0.847	Yes	Yes	√
	Data Storage Capacity	30	4.233	0.679	0.850	25	4.200	0.577	0.840	0.833	Yes	Yes	√
	Network Infrastructure Availability	30	4.233	0.679	0.850	25	4.280	0.542	0.860	0.863	Yes	Yes	√
Specific BIM Modelling Capacity	Internal Information Management Standards	30	4.500	0.630	0.900	25	4.360	0.860	0.870	0.630	No	Yes	Removed
	BIM Standards	30	4.333	0.758	0.870	25	4.400	0.646	0.880	0.792	Yes	Yes	√
	Data Classification and Naming Practices	30	4.100	0.885	0.820	25	4.200	0.646	0.840	0.792	Yes	Yes	√
	BIM Coverage (Uses) Capacity	30	3.467	0.860	0.690	25	3.480	0.872	0.700	0.620	No	No	Removed
	Model Maturity Capacity	30	3.933	0.907	0.790	25	3.960	0.611	0.790	0.813	Yes	Yes	√
	LOD/LOI Capacity	30	3.867	0.900	0.770	25	4.080	0.640	0.820	0.795	Yes	Yes	√
	Model Server Usage	30	3.400	1.037	0.680	25	3.240	0.779	0.650	0.697	No	No	Removed
Proposed Methodology	Suitability-BEP's for Project	30	3.900	0.923	0.780	25	4.040	0.539	0.810	0.855	Yes	Yes	√
	Innovativeness-BEP's for Project	30	3.533	0.819	0.710	25	3.440	0.712	0.690	0.747	Yes	No	Removed
	BIM Vendor Involvement and Support	30	3.600	0.770	0.720	25	3.840	0.625	0.770	0.805	Yes	Yes	√
	Suitability of Privacy and Security Plans	30	3.967	0.890	0.790	25	3.960	0.735	0.790	0.730	No	Yes	Removed
Stability Between Round 1 and 2 Spearman's rho [0.964** $p < 0.01$] ** Correlation is significant at the 0.01 level (2-tailed) [Acceptable agreement between rounds hence terminated at Round 2]													

The retained sub-criteria in the *Capacity and Resources* dimension were: *IT Vision and Mission, Quality of BIM Implementation Strategy, BIM Research and Development, Software Availability, Data Storage Capacity, Network Infrastructure Availability, BIM Standards, Data Classification and Naming Practices*, *Model Maturity Capacity*, *LOD/LOI Capacity, Suitability of BIM Execution Plans (BEP)* and *BIM Vendor Involvement and Support.* Open-ended responses suggest that many of the criteria in this dimension were eliminated as a result of overlaps in what they measure in principle.

7.3.5.3 Critical Culture and Attitude Related Criteria

The test of stability yielded a positive Spearman's rho [*rho* = 0.816, $p < 0.01$], indicative of significant and high degree of correlation, hence stability. All variables in this segment did not therefore need further testing in a subsequent round after the second round of Delphi survey administration. The results from the second round survey were then run through the test of consensus for critical qualification criteria as explained above. Three criteria were eliminated namely: reputation in relation to *Relationship with Principle Supplier (Satisfaction*) (Mean = 4.120 and r_{wg} = 0.653), *Youthfulness of Staff* (Mean = 2.360 and r_{wg} = 0.547) and *Number of Graduates in Firm* (Mean = 2.480 and r_{wg} = 0.703). After the removal of these criteria the remaining criteria considered as the most critical to BIM qualification were: *Performance on Past BIM projects (satisfaction), Technology Readiness (attitude and willingness), Awareness of BIM Benefits (in project context), Extent of IT Support to Core Business and Processes* within Firm and *Organisational Structure* (decentralisation). All the main criteria in this category were thus retained.

7.3.5.4 The Importance of Cost as a Qualification Criterion

Since the section for *Cost* criteria contained only one variable it was added to the *Culture and Attitude* dimension for the stability analysis. The test of consensus resulted in the retention of *Cost/Price of BIM Service* as a critical BIM qualification criterion. This is presented in Table 7.7.

Table 7.7: Determination of Critical Culture, Attitude and Cost Related Criteria

BIM Qualification Criteria			Delphi Round 1				Delphi Round 2				Agreement and Consensus Summary			
			N	Mean	Std. D	RII	N	Mean	Std. D	RII	Rwg	Consensus	Mean ≥3.5	Retained
Culture and Attitude	Reputation	Relationship with Principle Supplier (Satisfaction)	30	4.167	1.085	0.830	25	4.120	0.833	0.820	0.653	No	Yes	Removed
		Performance on Past BIM projects (Satisfaction)	30	4.167	0.699	0.830	25	4.040	0.539	0.810	0.855	Yes	Yes	√
	Technology Readiness	Attitude Towards New Technology/Willingness	30	4.067	0.868	0.810	25	4.200	0.500	0.830	0.847	Yes	Yes	√
		Youthfulness of Staff	30	2.300	0.988	0.460	25	2.360	0.952	0.470	0.547	No	No	Removed
		Number of Graduates in Firm	30	2.500	0.938	0.500	25	2.480	0.770	0.500	0.703	No	No	Removed
		Awareness of BIM Benefits	30	4.067	0.740	0.810	25	4.040	0.539	0.810	0.855	Yes	Yes	√
		Extent of IT Support to Core Business and Processes within Firm	30	4.067	0.640	0.810	25	4.120	0.526	0.820	0.861	Yes	Yes	√
	Organisational Structure	Organisational Structure - Level of Decentralisation	30	3.467	0.973	0.690	25	3.800	0.707	0.760	0.750	Yes	Yes	√
Cost		Cost/Price of BIM Service	30	3.667	0.884	0.730	25	3.920	0.702	0.780	0.753	Yes	Yes	√
Stability Between Round 1 and 2 Spearman's rho [0.816** $p < 0.01$] ** Correlation is significant at the 0.01 level (2-tailed) Acceptable agreement between rounds hence terminated at Round 2														

√ = Represents Retained Assessment Criteria

7.3.5.5 Summary of Delphi Results

As presented above all of the eleven proposed BIM qualification criteria were retained as critical to the pre-qualification or selection. Twenty eight (28) out of the total number (45) of sub-criteria proposed were also identified to be the most critical to the BIM qualification process for CSC. Based on a review of open-ended responses, it was realised that while some criteria were eliminated as a result of not being critical, others were eliminated as a result of participants' views that these criteria were strikingly similar to some of the other proposed qualification criteria.

7.4 THE GENERAL SURVEY (Quantitative - Part 2)

The general survey was used to ascertain the impact of the 28 critical BIM qualification criteria (from the Delphi study) on BIM delivery success. Delivery success was considered in three areas, namely, overall success, BIM modelling success and CSC success through BIM. In addition to modelling the relationship between BIM qualification criteria and delivery success, the mediating and moderating effect of project characteristics was also assessed. Each BIM qualification criterions importance as an assessment metric is also compared to its relative contribution to delivery success in practice. The procedure and quantitative techniques adopted for this phase of the research is explained together with a presentation of the results.

7.4.1 The Development of Survey Instrument

A questionnaire was found to be the most appropriate approach for data collection. According to Xiao (2002), questionnaires need to be '*respondent-friendly'* in order to increase the likelihood of response. The questionnaire designed in this study was, therefore, made simple together with clear guidelines and instructions to respondents. It was designed in several versions to enable distribution at respondent's convenience. This included a print version (for postal and self-administration), electronic form format (for emails) and an online version (for direct internet distribution).

The questionnaire was in four main parts. The first part solicited information about the respondents' background while the second required the background information concerning the CSC organisation and project being assessed. In the third part, respondents were asked to share their opinions on the influence of the 28 proposed BIM qualification criteria on BIM delivery success of a particular CSC organisation, on a current, or recent BIM-enabled project. Respondents were also asked to provide a performance assessment of this organisation in relation to the level of attainment of BIM success. The BIM delivery success indicators for the CSC were adopted from the review of indicators in the literature namely: BIM model quality; delivery within time; delivery within budget (cost); collaboration; coordination; and integration through BIM (*Section 4.3.5*).

The background information solicited, was mainly in relation to the professional expertise and experience of respondents in order to ensure the validity and reliability of responses. The sample questionnaire is attached in Appendix D.

7.4.2 Sampling of Survey Respondents

The survey aimed to solicit information from a wider sample in contrast with the interviews and Delphi study, where a much smaller sample, consisting of experts was required. The objective was to ascertain project participants' opinions based on a current or recent experience on a project in UK. However, as a result of time constraints, it was impossible to sample the entire population of UK CSC organisations. Thus, techniques had to be adopted to ensure that a sizeable but representative sample size was chosen for the survey. According to Oppenheim (1992), sampling techniques must be tailored to suit the context of data being collected. Random sampling is the most advocated approach for surveys of this nature (Creswell, 2003). Random sampling is a procedure that generally involves the systematic selection of respondents, such that each unit within the population has an equal chance of being selected (Oppenheim, 1992). It requires the identification of a population called the sample frame and involves the use of a statistical technique to determine a representative minimum sample size (Creswell, 2003). It is estimated that the entire CSC consists of up to 280,000 organisations, however very few of these organisations actually use BIM (BIS, 2013b). Though company registration databases are often used in construction management research to identify sample frames (Ankrah, 2007), it was deemed unsuitable for sampling CSC firms that use BIM. Thus, in view of the relative lack of information on exactly how many firms are currently using BIM in the CSC, the reliance on databases of registered companies was deemed inappropriate to identify potential participants. Other means of identifying participants were devised. These included similar techniques used for the identification of interview and Delphi participants. Included were extensive consultation of the internet, published case studies and online professional networks and groups to identify events, construction organisations and individual BIM professionals in the UK construction industry. A contact list was generated to aid invitation of survey participants. The range of professionals within these groups helped in targeting various segments and types of CSC organisations. After the identification of the sample frame, an appropriate technique (*section 7.4.2.1*) was adopted to determine the minimum sample size required for the study.

7.4.2.1 Sample Size Determination

In order to determine a suitable sample size, the following formula (Equation 7.3) from Creative Research Systems (2003) was applied. This formula has been used in the determination of minimum sample size by Ankrah (2007), Ahadzie (2007), Manu (2012) and Baba (2013).

Equation 7.3: Sample Size Determination Formula

$$ss = \frac{z^2 \times p(1-p)}{C^2}$$

Where:

ss = sample size;

z = standardised variable;

p = percentage picking a choice, expressed as a decimal; and

C = confidence interval, expressed as a decimal.

A confidence level of 95% was assumed, thus, resulting in a Z of 1.96. Furthermore, a confidence interval (c) of ±10% was assumed (Baba, 2013). Czaja and Blair (1996) recommend the use of *p* at 50% in order to ensure accuracy. Based on these assumptions, the minimum sample size was computed as follows (Equation 7.4):

Equation 7.4: Computation of Sample Size for General Survey

$$ss = \frac{1.96^2 \times 0.5(1-0.5)}{0.1^2}$$

$$ss = 96.04$$

From this computation the required number of respondents for the survey was determined as 96 CSC firms. However, the adequacy of this figure needs to be considered relative to the estimated total population. The estimates for the entire UK CSC was adopted (BIS, 2013b). This was achieved through the formula in Equation 7.5 (Czaja and Blair, 1996).

Equation 7.5: Adjusted Sample Size Formula

$$Adjusted\ ss = \frac{ss}{1 + \frac{ss-1}{Pp}}$$

Where:

Pp = population.

Based on the BIS (2013b) estimate of 280,000 CSC firms in UK, the adjusted sample size was then computed as shown in Equation 7.6.

Equation 7.6: Adjusted Sample Size Computation

$$Adjusted\ ss = \frac{96.04}{1 + \frac{96.04-1}{280{,}000}}$$

$$Adjusted\ ss = 96.01$$

The required sample size with reference to the total estimated population of the UK CSC remained at 96. It is further recommended that this is adjusted based on an estimation of response rates in similar studies (Baba, 2013). According to Ankrah (2007) and Baba (2013) a conservative rate of 20% is appropriate in order to adjust sample size for surveys intended within the UK construction industry. Based on this estimate, the sample size was adjusted to cater for possible non-response, as shown in Equation 7.7.

Equation 7.7: Computation of Survey Sample Size

$$Survey\ ss = \frac{Adjusted\ ss}{0.2} = \frac{96}{0.2}$$

$$Survey\ ss = 480$$

Having computed 480 as the target survey population, questionnaires were then distributed such that more than 480 construction professionals on BIM-enabled projects would have a random opportunity to respond. 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 and consist of a high number of UK professionals. Furthermore, 160 questionnaires were directly distributed to individuals in the generated contact list from the internet searches and solicitation of contacts from BIM events. These measures ensured that more than the required 480 respondents were approached at least. Follow-up messages and reminders were deployed to improve the response rate as recommended by Creswell (2009).

Sixty nine (69) survey responses were received after a three month administration exercise, out of which only 64 were deemed valid due to inconsistency and unacceptable levels of missing data. This represents a 13.33% response rate. This latter rate is within an acceptable range in comparison to similar studies where rates between, 8.82% to 15.42%, have been reported (Soetanto *et al.,* 2001; Sutrisna, 2004; Ankrah, 2007). In relation to the number of responses (64), similar figures have been relied for the conduct of multi-variant statistical analysis as replicated in this study. Ahadzie (2007) and Ankrah (2007) utilized 59 and 64 responses, respectively, from surveys where similar statistical analysis was involved. Table 7.8 presents a summary of the analysis of survey response.

Table 7.8: Response to General Survey

Description	**Individuals**		**Online Posts (groups and platforms - 330 to 10,000 members)**
	Postal/Self-Administered	Online	
Questionnaires Administered	50	110	15 (group posts)
Questionnaires Returned	17	52	
Total Questionnaires Returned	69		
Valid Returns Used for Analysis	64		
Computed minimum Survey *ss*	480		
Response Rate	13.33%		

7.4.3 Statistical Techniques for Preliminary Analysis of General Survey

Various quantitative data analysis techniques were employed to assess survey respondents' opinions concerning the impact of BIM qualification criteria on BIM delivery success in projects. The statistical techniques employed to achieve this are presented below.

7.4.3.1 Descriptive Statistics

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.

7.4.3.2 Relative Importance Index (RII) and Spearman's rank correlation coefficient

The relative importance indices of BIM qualification criteria in relation to their contribution to overall delivery success was computed to aid ranking of criteria. The procedure for RII is explained in *Section*

7.3.3.2. Spearman's coefficient (*rho*) as explained in *Section 7.3.4.2* was used to test for agreement between results from the Delphi survey and the general survey. Spearman's *rho* is a non-parametric test for statistical dependence between two variables (Jamieson, 2004). In this study, it was used to test for differences in criteria importance when considered as BIM qualification criteria when compared to their perceived contribution to BIM delivery success.

7.4.3.3 Weighted Mean Contribution

The weighted contribution of variables to delivery success is computed through a summation of their mean weighted contribution (Xia and Chan, 2012). Giel and Issa (2015) similarly used this to assess priority weighting 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 7.8.

Equation 7.8: Weighted Mean Contribution

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

Where:

W_i = the weighted proportion of the assessment score used for a particular BIM competency factor;

u_i = the mean importance rating of a particular BIM competency factor; and

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

7.4.3.4 Data Screening

Missing data is a common occurrence in surveys. They may affect validity of results (Hair *et al.*, 2010). Consequently, all returned responses were screened thoroughly to allow usage of only sufficiently completed and reliable questionnaires. Since the online version made use of *'forced- response'* there was automatic screening of responses with missing data on the online version of the survey. Questionnaire responses with excessive missing data from the paper based survey were, however, removed before data analysis.

The screening of data resulted in reliance on only 64 responses which were largely complete except for two cases which had a few missing data points. The questionnaire responses with a few cases of missing data were factored into the data analysis through SPSS v.19 package functions.

7.4.4 General Survey Results

The results from the survey are presented below. The background of respondents, organisations and projects is presented first followed by the descriptive analyses. The comparison between Delphi and survey results is presented and then followed by inferential statistical modelling of the relationship between variables.

7.4.4.1 General Survey Respondents' Backgrounds

As summarised in Table 7.9, the majority of respondents were BIM Managers or Technicians (31.3%) followed by Project, Construction Managers (15.6%) and Quantity Surveyors (15.6%). Majority of respondents (46.9%) had between 11-15 years industry experience. Many respondents (35.9%) also had between 4-6 years' experience working with BIM or other relevant digital construction technologies (VDC).

With regard to the educational qualifications of respondents, 42.2% of respondents were holders of a Bachelor's degree as their highest educational qualification with a substantial number of respondents holding higher degrees such as Masters (29.7%) or a Doctorate (7.8%). This is indicative of a substantially experienced and knowledgeable group of respondents whose opinions are valuable, reliable and relevant to the research.

Table 7.9: General Survey Respondent's Background

		Frequency	%	Cumulative %
Profession	Architect	5	7.8	7.8
	Engineer	8	12.5	20.3
	Project /Construction Manager	10	15.6	35.9
	Quantity Surveyor	10	15.6	51.6
	BIM Manager/Technician	20	31.3	82.8
	Academic	9	14.1	96.9
	Other	2	3.1	100
Construction Industry Experience	1-5 years	9	14.1	14.1
	6-10 years	17	26.6	40.6
	11-15 years	30	46.9	87.5
	Over 15 years	8	12.5	100
BIM or Virtual Digital Construction Experience	1-3 years	21	32.8	32.8
	4-6 years	23	35.9	68.8
	7-10 years	19	29.7	98.4
	Over 10 years	1	1.6	100
Qualification	GCS	2	3.1	3.1
	HND	11	17.2	20.3
	Bachelor's Degree	27	42.2	62.5
	Master’s Degree	19	29.7	92.2
	Doctorate	5	7.8	100

7.4.4.2 Background of Supply Chain Organisations Assessed in Survey

Respondents were required to execute a performance evaluation of a firm with which they have worked closely on a recent BIM project. This was to establish their opinion about the influence of the BIM qualification attributes particular to this firm on their BIM delivery success on the project.

The attributes assessed were based on the critical BIM qualification criteria derived from the Delphi Study. A summary of the CSC organisations that were assessed by survey respondents is presented below in Table 7.10.

Many of the organisations assessed belong mainly to the top or middle tier of the CSC. Majority were Design Consultants with Architects representing 34.4%, while Engineering Consultants represented 25% of the organisations assessed. Among the fewest types of organisations assessed were Material Suppliers (4.7%) and Sub-Contractors (6.3%).

Table 7.10: Background of Supply Chain Organisations Assessed By Survey Respondents

		Frequency	%	Cumulative %
Type of Firm	Main Contractor	10	15.6	15.6
	Sub-Contractor	4	6.3	21.9
	Design Consultant (Architecture)	22	34.4	56.3
	Design Consultant (Engineering)	16	25.0	81.3
	Consultant (Other)	3	4.7	86.0
	Material/Product Supplier	3	4.7	90.7
	Research/Case Study	2	3.1	93.8
	Other	4	6.3	100
Firm Size	Less than 50 Employees	19	29.7	29.7
	50-250 Employees	26	40.6	70.3
	Over 250 Employees	19	29.7	100
Firm's General Experience	5-10 years	12	18.8	18.8
	11-15 years	23	35.9	54.7
	16-20 years	15	23.4	78.1
	Over 20 years	14	21.9	100
Firm's BIM or Virtual Digital Construction Experience	Less than 3 years	29	45.3	45.3
	3-6 years	28	43.8	89.1
	7-10 years	7	10.9	100
Supply Chain Position	Top Tier	19	29.7	29.7
	Middle Tier	40	62.5	92.2
	Lower Tier	5	7.8	100

7.4.4.3 Background of Supply Chain Organisations Assessed in Survey

The background of projects on which these firms were assessed is summarised in Table 7.11. From the responses, 19.3% of the projects were notably large with estimated values in excess of £50 million. Significant number was (80.6%), however, representing less than £50 million, in value, with more than half above £25 million.

According to respondents, most of the projects (40.3%) showed intermediate level of CSC integration with a substantial (35.5%) number of the project CSC's considered as fragmented. Most of the projects had some middle tier CSC involvement in the project BIM process with only 1.6% reporting lower tier participation. A large proportion (90.3%) of the projects surveyed were buildings, with only 9.7 % being civil engineering projects.

Table 7.11: Background Details of Projects Assessed by Survey Respondents

		Frequency	%	Cumulative %
Project Size	Less than £25M	30	48.4	48.4
	£26 - £50M	20	32.3	80.6
	£51M-£75M	6	9.7	90.3
	£76M-£100M	3	4.8	95.2
	Over £100M	3	4.8	100.0
Supply Chain Integration	Highly Fragmented	3	4.8	4.8
	Some Fragmentation	22	35.5	40.3
	Intermediate	25	40.3	80.6
	Fairly Integrated	12	19.4	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

7.4.4.4 Assessment of the Complexity of Surveyed Projects

Respondents were required to present an assessment of the level of complexity of the projects assessed in four areas, BIM Task responsibility of assessed CSC organisation, project BIM complexity, BIM maturity and product or facility complexity (in terms of design and form) (Figure 7.2).

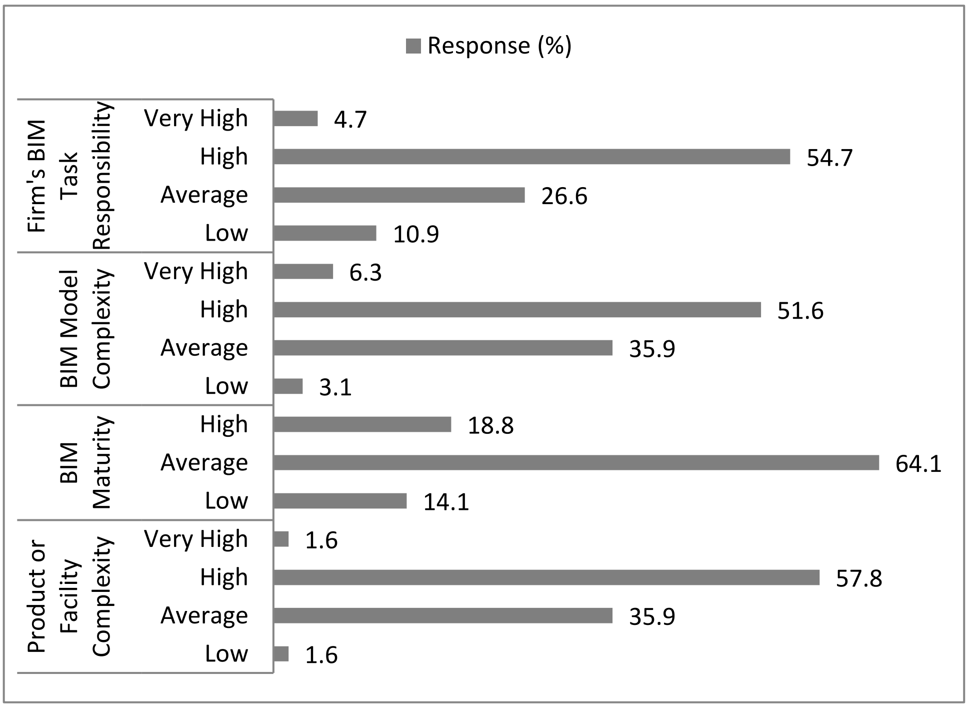


Figure 7.2: Complexity of Projects Assessed by Survey Respondents

From Figure 7.2, it is clear that 54.7% of CSC organisations assessed demonstrated a high level of BIM responsibility on the projects considered for the assessment. About half (51.6%) of the project BIM models were considered as highly complex, while 64.1% were considered as average in terms of BIM maturity (level 2). More than half (57.8%) of the facilities being modelled were considered to be complex in terms of design, form or functionality.

7.4.5 Influence of BIM Qualification Criteria on Overall BIM Delivery Success

From the analysis of the survey data, all attributes proposed as BIM qualification criteria were regarded as influential on the BIM delivery success by CSC organisations on projects. A significant number qualification criteria recorded mean ratings ≥ 3.5, interpreted on the rating scale as *'very influential'*. A summary of the results is presented in Table 7.12.

Staff Experience (Mean = 3.883) emerged as the most important influencer of BIM delivery success. This is followed by *Specific BIM Modelling Capacity* (Mean = 3.426), *Organisation's Experience* (Mean = 3.399) and *Technology Readiness* (Mean = 3.354). The sub-criteria regarded as most highly influential 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 *LOD/LOI Capacity.*

Some other criteria had means 1.5≤ mean ≤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. Despite their low level of influence, they still remain influential with none of the criteria presented regarded as not influential on BIM delivery a success.

Table 7.12: Descriptive Analysis of Influence of BIM Criteria on Overall Delivery Success

Variables (BIM Qualification Criteria)		Statistics						Degree of Influence*		
		N	Range	RII	Rank	Mean	SD	SI	I	VI
Competence	**Professional and Academic Qualifications** (Mean = 3.067)									
	Key Technical Staff BIM Qualifications	64	4	0.588	21	2.938	1.067		√	
	BIM Staff Availability for Project	64	4	0.669	14	3.344	0.946		√	
	Organisation's BIM Accreditations and Certifications	64	4	0.478	28	2.391	1.229	√		
	Organisation's BIM Training Arrangements	64	4	0.719	7	3.594	1.065			√
	Staff Experience (Mean = 3.883)									
	Managerial Staff BIM Experience	64	4	0.713	10	3.563	1.125			√
	Key Technical Staff BIM Experience	64	3	0.841	1	4.203	0.858			√
	Organisation's Experience (Mean = 3.399)									
	BIM Software Experience	64	3	0.731	5	3.656	0.781			√
	Past BIM Project Experience	64	3	0.719	7	3.594	0.921			√
	BIM Experience on Similar Project	64	4	0.603	19	3.016	1.076		√	
	Internal Use of Collaborative IT	64	4	0.666	15	3.328	0.977		√	
Capacity and Resources	**Administrative and Strategic Capacity** (Mean = 3.333)									
	IT Vision and Mission	64	4	0.631	18	3.156	0.979		√	
	Quality of BIM Implementation Strategy	64	3	0.719	7	3.594	0.849			√
	BIM Research and Development	64	4	0.650	16	3.250	1.084		√	
	Technical (Physical) Resources (Mean = 3.068)									
	Software Availability	64	4	0.700	11	3.500	0.960			√
	Data Storage	64	4	0.566	24	2.828	0.901		√	
	Network Infrastructure	64	4	0.575	23	2.875	0.951		√	
	Specific BIM Modelling Capacity (Mean = 3.426)									
	BIM Standards	64	4	0.725	6	3.625	1.266			√
	Data Classification and Naming Practices	64	4	0.700	11	3.500	1.039			√
	Model Maturity Capacity	64	4	0.578	22	2.891	1.143		√	
	LOD/LOI Capacity	64	4	0.738	4	3.688	1.125			√
	Proposed Methodology (Mean = 3.149)									
	Suitability of Proposed BIM Execution Plans for Project	64	3	0.769	2	3.844	0.801			√
	BIM Vendor Involvement and Support	64	4	0.491	26	2.453	1.181	√		
Culture and Attitude	**Reputation** (Mean = 2.453)									
	Performance on Past BIM Projects	64	4	0.491	26	2.453	1.181	√		
	Technology Readiness (Mean = 3.354)									
	Attitude Towards New Technology/Willingness	64	4	0.672	13	3.359	1.060		√	
	Awareness of BIM Benefits	64	3	0.747	3	3.734	0.802			√
	Extent of IT Support to Core Business and Processes	64	4	0.594	20	2.969	1.098		√	
	Organisational Structure (Mean = 2.781)									
	Level of Decentralisation	64	4	0.556	25	2.781	1.105		√	
Cost (Mean = 3.188)										
Price of BIM Service		64	4	0.638	17	3.188	0.906		√	

**SI –Slightly Influential; I –Influential; and VI – Very Influential*

7.4.5.1 Reliability of Scales

Cronbach's Alpha is a test statistic used in assessing the reliability of scales used in measurement of data (Field, 2005). The Cronbach's Alpha was computed to assess the reliability of the scales used for the measurement of the influence of qualification criteria yielding a highly acceptable value of 0.93 as recommended in Field (2005).

7.4.5.2 Assessment of the CSC Organisations BIM Delivery Success

As part of the assessment of CSC organisations, respondents were asked to rate the extent to which they believe they were successful in the delivery of BIM. Six specific success indicators were used to assess BIM delivery success in the CSC context. These were attainment of BIM deliverables within budget (cost), schedule (time) and the quality of BIM models delivered. The other areas assessed were the extent of achievement of collaboration, coordination and integration of the project CSC through BIM.

From the analysis, most of the firms were adjudged with a performance score of *'Very Good'* in relation to budget (Mean = 4.656; S.D = 0.946) as shown in Table 7.13. In the opinion of respondents most firms achieved of a good degree of success in the delivery of quality (Mean = 4.297; S.D = 1.079), schedule (Mean = 4.094; S.D = 1.123) and collaboration (Mean = 3.922; S.D = 1.088). The two areas where high level of success was not attained were coordination (Mean = 3.469; S.D = 1.038) and the integration (Mean = 3.313; S.D = 1.111) of the CSC through BIM. Furthermore, the high levels of standard deviations (SD = 0.946 - 1.123) is indicative of high level of variability in the performance assessment. Despite this level of variability, Cronbach's Alpha (0.810) was indicative of acceptable reliability of the scales used for assessing success.

Table 7.13: The Attainment of BIM Delivery Success by CSC Organisations in Survey

Variables	**Statistics**						**Extent of Attainment on Project**		
	N	Range	Min	Max	Mean	Std. D	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	√		

7.4.5.3 A Comparison between Criteria's BIM Qualification Importance and Contribution to Delivery Success

The RII of criteria presented as variables in the general survey was based on their perceived contribution to BIM delivery success. On the other hand the RII of criteria in the Delphi survey was based on practitioners' views with regards to their criticality as a qualification metric. A comparison was, therefore, made between the RII rankings from the two surveys to identify whether statistically significant differences (Table 7.14) existed in participants' perceptions.

A test of correlation (agreement) between the RII's from the survey and Delphi studies revealed non-significant degrees of association: competence criteria [*rho* = -0.018, $p > 0.05$]; capacity and resources criteria [*rho* = -0.047, $p > 0.05$]; culture, attitude and cost criteria [*rho* = 0.058, $p >= 0.05$] and overall [*rho* = 0.039, $p > 0.05$]. From these results, it is evident that despite the similarity in criteria importance ratings, there was no statistically significant correlation between the perceived importance accorded to attributes when considered as qualification criteria (evaluation metric) and their perceived role in actual delivery success in practice. A detailed review of individual variables revealed that despite the ranking of some criteria as most important in the BIM qualification process, they were not considered as important in terms of their contribution to overall delivery success.

Table 7.14: Comparison of Criteria Importance - Delphi Study and General Survey

Qualification Criteria			Contribution to Delivery Success		Importance as Qualification Criteria		Agreement (S - RII and D - RII)
			Survey RII	Rank	Delphi RII	Rank	
Competence	Qualification	Key Technical Staff BIM Qualification	0.588	21	0.792	21	*rho* = -0.018 $p > 0.05$
		BIM Staff Availability for Project	0.669	14	0.803	19	
		Organisation's BIM Accreditations and Certifications	0.478	28	0.805	17	
		Organisation's BIM Training	0.719	7	0.750	27	
	Staff Experience	Managerial Staff BIM Experience	0.713	10	0.897	1	
		Key Technical Staff BIM Experience	0.841	1	0.792	21	
	Organisation Experience	BIM Software Experience	0.731	5	0.839	10	
		Past BIM Project Experience	0.719	7	0.833	11	
		BIM Experience on Similar Project	0.603	19	0.822	14	
		Internal Use of Collaborative IT Systems	0.666	15	0.855	4	
Capacity and Resources	Administrative and Strategic Capacity	IT Vision and Mission	0.631	18	0.763	25	*rho* = -0.047 $p > 0.05$
		Quality of BIM Implementation Strategy	0.719	7	0.833	11	
		BIM Research and Development	0.650	16	0.822	14	
	Technical (Physical) Resources	Software Availability	0.700	11	0.847	8	
		Data Storage	0.566	24	0.833	11	
		Network Infrastructure Availability	0.575	23	0.863	2	
	Specific BIM Modelling Capacity	BIM Standards	0.725	6	0.792	21	
		Data Classification and Naming Practices	0.700	11	0.792	21	
		BIM Modelling Maturity	0.578	22	0.813	16	
		Model LOD/LOI Capacity	0.738	4	0.795	20	
	Proposed Methodology	Suitability of Proposed BIM Execution Plans for Project	0.769	2	0.855	4	
		BIM Vendor Involvement and Support	0.491	26	0.805	17	
Culture and Attitude	Reputation	Performance on Past BIM Projects (satisfaction)	0.491	26	0.855	4	*rho* = 0.058 $p > 0.05$
	Technology Readiness	Attitudes and Willingness	0.672	13	0.847	8	
		Awareness of BIM Benefits	0.747	3	0.855	4	
		Extent of IT Support to Core Business and Processes within Firm	0.594	20	0.861	3	
	Organisational Structure	Level of decentralisation	0.556	25	0.750	27	
Cost		Cost/Price of BIM Service	0.638	17	0.753	26	

From the analysis, the following criteria were regarded as high contributors to success in practice, however, these same criteria are given lower levels of consideration when being used as qualification criteria for the CSC in the U.K: *Key Technical Staff BIM Experience* [1(21)]; *LOD/LOI Capa*city [4(20)]; *BIM Standards* [6 (21)]; *Organisation's BIM Training* [7 (27)]; *Data Classification and Naming Practices* [11(21)].

The following were also ranked as very important criteria for BIM qualification of the CSC but were, however, ranked relatively lower in terms of their perceived contribution to overall BIM delivery success: *Managerial Staff BIM Experience* [1(10)]; *Internal Use of Collaborative IT Systems* [4(15)]; *Network Infrastructure Availability* [2(23)]; *Reputation of Organisation (performance on past projects)* [4(26)]; and *Extent of IT Support to Core Business and Processes within Firm* [3(20)].

The finding indicates that *Competence* as well as *Resources and Capacity* criteria are both generally considered as important during qualification as well as contributors to delivery success. Culture and attitude criteria (*Reputation* and *Extent of IT Support to Core Business and Processes*) as well as physical technological infrastructure (*Network Infrastructure*) are also considered highly important during qualification of the CSC, however, perceptions about the extent to which they contribute to success in practice is lower than the prominence given to them as evaluation criteria. They are not generally perceived as among the highest contributors to delivery success in practice when compared to process maturity and competence related criteria (*Key Technical Staff BIM Experience*, *LOD/LOI Capability*, *BIM Standards*, *Organisation's BIM Training and Data Classification and Naming Practices*). The test for similarity in participant rating of criteria between Delphi and general survey is presented in Table 7.14.

7.4.6 Weighted Contribution of Criteria to Overall BIM Delivery Success

Despite identifying the BIM qualification criteria importance to delivery success, the descriptive data does not provide adequate insight in relation to criteria weighted contribution to delivery success. The weighted contribution is computed based on mean ratings using Equation 7.8.

The overall weighted contribution of each criterion represents their combined contribution to delivery success relative to each other. This takes into account the number of sub-criteria representing the particular criteria. This method is recommended where weighted contribution of criteria is required as part of an index or framework (Giel and Issa, 2014). This is presented in Table 7.15.

Table 7.15: Overall Weighted Contribution of Criteria to Delivery Success

BIM Qualification Criteria		Sub Criteria	Mean	Qualification Criteria Weighted Contribution to Overall Success - W_i (%)				
				Local	Global	Local	Global	
Competence	Professional and 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	3.594	29.30	3.94			
	Staff Experience	Managerial Staff BIM Experience	3.563	45.88	3.90	23.09	8.50	
		Key Technical Staff BIM Experience	4.203	54.12	4.60			
	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			
Capacity	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			
	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	2.875	31.24	3.15			
	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 Capacity	2.891	21.09	3.17			
		LOD/LOI Capacity	3.688	26.91	4.04			
	Proposed Methodology	Suitability of Proposed BIM Execution Plans for Project	3.844	61.04	4.21	16.06	6.90	
		BIM Vendor Involvement and Support	2.453	38.96	2.69			
Culture and Attitude	Reputation	Performance on Past BIM Projects (satisfaction)	2.453	100.00	2.69	16.06	2.69	16.75
	Technology Readiness	Attitude and 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/Processes	2.969	29.50	3.25			
	Organisational Structure	Level of Decentralisation	2.781	100.00	3.05	18.18	3.05	
Cost		Cost/Price of BIM Service	3.188	100.00	3.49	100.00	3.49	3.49

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%) and *Technology Readiness* (11.02%). 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%).

7.5 MODELLING THE INFLUENCE OF BIM QUALIFICATION CRITERIA ON DELIVERY SUCCESS

Multivariate statistical modelling techniques were used to model the relationship between the attributes relied on as BIM qualification criteria and key BIM delivery success indicators in the CSC context. This was achieved through multiple linear regression analysis of survey data. This process included the construction of an index of BIM qualification criteria and success indicators. The eleven main BIM qualification criteria were modelled as independent variables on success indicators representing the dependent variables. Two dimensions of success indicators were drawn from the literature (*Section 4.3.3* and *4.3.5*). 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. This dimension of success included the following variables collaboration, coordination and integration of CSC through BIM. The procedure for modelling these relationships is presented together with the analysis and results. The role of individual CSC organisation and project characteristics on the attainment of success was also analysed. This was achieved through the one-way analysis of variance (ANOVA) as well as mediation and moderation analysis.

7.5.1 Statistical Techniques for Modelling BIM qualification Criteria Influence

Inferential and multivariate data analysis techniques were employed to assess construction project participants' perceptions concerning the impact of various BIM qualification criteria on specific BIM delivery success areas. This multivariate analysis provided deeper exploration of data as explained below.

7.5.1.1 Pearson's Product-moment Correlation Coefficient

Pearson's correlation coefficient denoted by (*r*) was used to establish linear relationships between variables. This is a measure of the linear correlation between two variables X and Y (Field, 2005). Correlations are often used to test relationships between variables in order to assess whether or not the rank order of variables are related (Field, 2000). Pearson's '*r*' is widely used within construction management research (Baba, 2013; Bashir, 2013) and has been previously applied in the study of relationships between BIM capability criteria (Kam *et al.,* 2014).

In this study, Pearson's correlation was used to measure the relationship between BIM qualification criteria, success indicators and project complexity characteristics. It was also used to check intra-variable relationships in order to identify whether or not some factors explained the same effect. Similar to all statistical correlation measures, coefficient values (*r)* lie between +1 and −1 with values closer to +1 denoting positive correlation, 0 denoting no correlation, while −1 denotes negative correlation. The variables studied were composite indices (*Section* 7.5.2.1), thus making *'r'* suitable despite its non-parametric nature. The equation to compute the Pearson's correlation coefficient is proposed by Field (2005), as presented in Equation 7.9.

Equation 7.9: Pearson's Product-moment Correlation Coefficient

$$r = \frac{\sum_{i-1}^{n}(x-\bar{x})(y-\bar{y})}{(1-n)S_x S_y}$$

Where:

x and y = the pairs of variables being considered;

$\bar{x}$ and $\bar{y}$ = the means of x and y respectively;

S_x and S_y = represent the standard deviations of x and y respectively; and

n = the sample size.

Relationships in the correlation analysis do not, however, confirm causality *per se* (Field, 2000). Therefore, it if often advised that further analysis is performed. Correlation is, however, considered as precursor for further inferential analysis (Ahadzie, 2007). Kam *et al.* (2014) applied correlation analysis to identify associations between BIM assessment criteria and overall project performance in order to improve the development of an assessment tool for BIM projects. In another study, Mom *et al.* (2014) used this to study the relationship between BIM CSFs and selected success indicators within construction organisations. Ankrah (2007), on the other hand, employed correlation analysis to identify linear relationships prior to conducting a more robust multiple regression analysis. Similar procedure to Ankrah (2007) was followed in this study.

7.5.1.2 Multiple Linear Regression

The multiple linear regression analysis is used for the development of predictive models for BIM delivery success with BIM qualification criteria as the predictors. Other techniques such as Multivariate Discriminant and Logistics Regression Analysis were not considered because the intention was not to predict categorical membership of dichotomy (being successful delivery or non-successful delivery), but rather a wider range of performance scores for success. Another method, which was not used, is the Artificial Neural Networks (ANN) because of limited explanatory powers (Al-Zahrani, 2013). Multiple regression analysis is one of the most popular for predicting performance across several independent variables and a single dependent variable (Hair *et al.,* 1998). Thus, multiple regression aids the identification of one or more variables based on their explanatory powers (influence over a dependent variable) (Blaikie, 2003). This technique estimates the relative magnitude of the contribution of each predictor variable to noticeable changes in the dependent variable. It can also be used to ascertain the unit contribution of several variables on the dependent variable (Brace *et al.,* 2003). Based on classical linear regression modelling, the relationship between the predicted outcomes Y_p and predictor variables (X_1, X_2, X_{k-1}, X_k) is expressed as follows (Equation 7.10).

Equation 7.10: Regression Model Equation

$$Y_p = \alpha + \beta_1 X_1 + \beta_2 X_2 + \cdots \beta_{k-1} X_{k-1} + \beta_k X_k + c$$

Where:

α = a constant on the y-axis;

β_1 to β_n = coefficients chosen to minimise the sum of squared discrepancies between the predicted and obtained values of Y_p;

c = the error term of random variable with mean 0 and variance σ^2; and

K = the number of independent variables.

The Stepwise Selection Method: The stepwise method in multiple linear regression is adopted in this study. Stepwise selection allows the model to reduce the variables to the most relevant predictors after iterative rounds where all variables are entered in the model in turns (Brace *et al.,* 2003). Each variable is entered in sequence and its value assessed to identify only variables with significant contributions. It helps ensure that the regression output consists of the most parsimonious set of predictor variables from the regression model (Field, 2005).

Assumptions of Regression: The conduct of a multiple regression analysis must be premised on meeting a number of assumptions. These associated assumptions must be met to guarantee the adequacy, reliability and predictive capacity of a regression model in a real world scenario (Hair *et al.*, 2006). The widely accepted assumptions include:

- **Linearity of the relationship between outcome and predictor variables -** In multiple regressions, it is assumed that the relationship between the independent and dependent variables is linear. This can be assessed by plotting the outcome against the predictor variables (Hair *et al.,* 2006). When data points generally cluster closely around a straight line, it indicates existence of linear relationships between outcome and predictor variable (independent variables) (Ahadzie, 2007). Random distribution of data points in a residual plot is also indicative of linearity in the relationship between outcome and predictor variable (Hair *et al.,* 1998; Field, 2005). Alternative regression approaches such as the introduction of polynomial terms could, however, be considered when the linearity assumption is violated.

- **Constant variance of the error terms** - Heteroscedasticity refers to scenarios where variability of a variable is unequal across the range of values of a second variable. This phenomenon is described as one of the most prevalent violations of multiple linear regression rules (Field, 2000). It can be diagnosed from the plots of residuals against the predicted outcome values. Noticeable and peculiar patterns (triangle or diamond-shaped) is often evidence of this violation (Hair *et al.*, 1998). Thus, an ideal plot shows randomly distributed points.

- **Independence of the error terms:** Another assumption in multiple regression is for uncorrelated residuals of the independent variable. Autocorrelation may exist where residual terms are not independent (Field, 2000). The Durbin-Watson test is recommended for testing this assumption. The test statistic varies between 0 and 4, with the value of 2 regarded as the most ideal (Field, 2005). Thus, values in the range of 1.5 - 2.5 or closer to this range, are most desirable. Values less than 1.5 (< 1.5) are indicative of positive autocorrelation which is, however, usual (Field, 2000). Values greater than 2.5 (> 2.5) indicate negative autocorrelation. Generally, values must not vary radically away from the acceptable range as a rule of thumb (Hair *et al.,* 2006).

- **Normality of the error term distribution:** One of the critical assumptions of multiple regression analysis is the normality of the predictor and outcome variables (Hair *et al.*, 1998). This can be assessed from a plot of a histogram of residuals. A bell-shaped residual curve from the plot of the histogram is indicative of a normal distribution (Field, 2000). In addition to this, a normal probability plot (P-P plot), which compares the standardised residuals with a normal distribution is often examined (Field, 2005). Normal distribution is often evidenced when the residual line closely lies on the plotted diagonal line (Hair *et al.*, 2006).

According to Hair *et al.* (1998), a critical indicator of prediction errors is the residual. The residual is the difference between the observed and predicted values for the outcome variable. Statistical analysis should, therefore, be performed on the residuals to identify the performance of a regression model in relation to the violation of the stated assumptions as described. According to Field (2000), the validity of predictions of a regression model is dependent on meeting these assumptions. Thus, when a particular regression model meets these assumptions, it shows the model is reliable and adequately reflects the population. Multiple regressions have been extensively used in the study of relationship between various factors and success in construction management. Doloi (2009a) adopted multiple linear regressions to investigate the impact of pre-qualification criteria on project success. Ankrah (2007) identified the influence of culture on project success through multiple linear regressions. Ahadzie (2007) applied multiple regressions to predict project managers performance based on their competency. All the cited studies examined and modelled the relationships between similar predictor and outcome variables based on construction practitioner's perceptions as adopted in this study.

7.5.1.3 The one-way analysis of variance (ANOVA)

The one-way analysis of variance (ANOVA) is used to determine whether there are any significant differences between the means of three or more independent groups within a data set (Field, 2000). ANOVA was used to analyse whether certain CSC firm characteristics could be statistically differentiated in relation to the attainment of BIM delivery success on projects. Specifically, the ANOVA tests the null hypothesis expressed in Equation 7.11:

Equation 7.11: The main Hypothesis of ANOVA

$$H_0: u_1 = u_1 = u_3 \cdots = u_k$$

Where:

μ = group mean; and

k = number of groups.

If the one-way ANOVA returns a significant result then the alternative hypothesis (H_A) is accepted. The H_A indicates that at least two group means are significantly different from each other. This test, however, assumes normally distributed data, otherwise, nonparametric procedures such as the Kruskal-Wallis and Mann-Whitney tests should be considered (Field, 2005). ANOVA has been applied to identify the effect of individual firm characteristics on the attainment of benefits from integrated information systems in construction firms (Tatari, 2009). This was achieved through a test of statistical differences in the means between groups under each category (firm characteristic). In this study ANOVA is applied to compare differences in perceptions with regards to the influence of qualification criteria across different CSC organisational demographics.

7.5.2 Index Construction for Multivariate Analysis

Drawing on the preliminary findings, an index for assessing the qualification criteria and success outcomes is developed. This is used to statistically convert a range of distinctive dependent variables (BIM qualification criteria) into a single variable as well as convert outcome variables (success). In addition to making data set manageable, the construction of an index further aids in meeting key assumptions of multiple regression analysis (Ahadzie, 2007). The construction of an index is used to aid the aggregation of several items that measure a similar concept (Blaikie, 2003). For the purposes of multiple regressions, an index is the most appropriate approach to structuring multiple, but distinctly related concepts into a single unique item (Hait *et al.,* 1998). An index should be combined to form a linear composite function, where each constituent item is weighted to reflect its importance within the underlying concept (Meyers *et al*., 2005; Ahadzie, 2008). However, according to Babbie (1990) equal weighting should be applied where there is no compelling reason. The following weighted composite index equation (Equation 7.12) is used in the index construction for this study (Meyers *et al.,* 2005).

Equation 7.12: Formula for Construction of Index

$$Weighted\ Composite = W_1x_1 + W_2x_2 + W_nx_n + W_{n-1}x_{n-1}$$

Where:

x = Constituent index item;

W = the weighted importance of the item to index.

Index construction must additionally satisfy certain requirements. According to Babbie (1990), in order to ensure face validity, each item included in the index should closely relate to the variable it purports to measure. Also, in order to satisfy unidimensionality, each item must represent only one concept, thus one item should not be used more than once (Meyers *et al.,* 2005). Therefore, no questionnaire item was included in more than one of the indices constructed.

7.5.2.1 Construction of Composite Index Research Variables

New variables were computed as indices for the research variables, which had more than one constituent elements or sub criteria. This included qualification criteria (predictor variables), success delivery (outcome variables) and project complexity characteristics (moderating and mediating variables). All items (sub-criteria) retained as part of the Delphi study were used as index items for a composite criteria representing the main BIM qualification criteria categories generated from the interviews. As recommended by Meyers *et al*. (2005), the weighted contribution generated for these items were applied in the index construction (Table 7.15). These were then aggregated within the distinctive main criteria areas.

To generate a holistic view of success in the context of the research, indices for two categories of success in the use of BIM were constructed. These were overall BIM modelling success (BIM quality, delivery of BIM on schedule and within budget) and CSC success through BIM (collaboration, coordination and integration through BIM). As argued by Xiao (2002) and Ankrah (2007), individual constituents of success must not be considered at the expense of the others. Thus equal weighting was applied in the construction of indices for success variables. Finally, an index was constructed for two categories of complexity namely '*project BIM complexity'* (product or facility complexity (design), project BIM model complexity and BIM Task responsibility) and '*CSC complexity'* (level of supply chain integration and supply chain Involvement in BIM process). Following Babbie's (1990) recommendations, equal weighting was similarly applied to complexity since there was no compelling reason to vary the weighted importance of each constituent item. Variables without several constituent items were not converted to indices including cost, reputation and organisational structure and project size (as a complexity characteristic). The details of the constituent items used in the construction of indices for survey variables are presented (Appendix F1).

7.5.3 Correlation between BIM Qualification Criteria and Success

Pearson's correlation (r) was used as an initial assessment to identify existing relationships between variables and also as a precursor for further inferential analysis (Ahadzie, 2007). The results of this analysis are presented in the next section.

7.5.3.1 Relationship between BIM Qualification Criteria and the Attainment of Success

Pearson's correlation coefficients (r) were generated to identify relationships between attributes used as BIM qualification criteria and the attainment of BIM delivery success. All qualification criteria were found to have a positive association with BIM delivery success overall as shown in Table 7.16. *Professional and Academic Qualifications* recording the most significant level of association ($r = 0.520$; $p < 0.01$) with BIM modelling success while *Cost* recorded the least ($r = 0.283$; $p < 0.05$). With regards to the specific success areas, the delivery of quality BIM models had the highest number of significant associations. Only *Cost* recorded a non-significant association with the delivery of quality ($r = 0.144$; $p > 0.05$). The qualification criteria with the most significant association was *Staff Experience* ($r = 0.602$; $p < 0.01$).

A total of five qualification criteria recorded significant associations with the delivery of BIM on schedule with the most association being with *Proposed Methodology* ($r = 0.475$; $p < 0.01$).

Table 7.16: Correlation between BIM Qualification Criteria and Key BIM-CSC Success Indicators

		BIM Modelling Success	Supply Chain Success through BIM	BIM Delivery Quality	BIM Delivery on Schedule	BIM Delivery Within Budget	Supply Chain Collaboration Through BIM	Supply Chain Coordination Through BIM	Supply Chain Integration Through BIM
Qualification	Pearson Correlation	**0.520****	0.199	**0.552****	**0.437****	**0.301***	0.163	0.174	0.165
	Sig. (2-tailed)	**0.000**	0.114	**0.000**	**0.000**	**0.016**	0.197	0.168	0.193
	N	**64**	64	**64**	**64**	**64**	64	64	64
Staff Experience	Pearson Correlation	**0.518****	**0.308***	**0.602****	**0.281***	**0.404****	**0.327****	0.12	**0.311***
	Sig. (2-tailed)	**0.000**	**0.013**	**0.000**	**0.025**	**0.001**	**0.008**	0.344	**0.012**
	N	**64**	**64**	**64**	**64**	**64**	**64**	64	**64**
Organisation Experience	Pearson Correlation	**0.430****	0.213	**0.461****	**0.251***	**0.356****	0.196	**0.282***	0.068
	Sig. (2-tailed)	**0.000**	0.091	**0.000**	**0.045**	**0.004**	0.121	**0.024**	0.594
	N	**64**	64	**64**	**64**	**64**	64	**64**	64
Administrative and Strategic Capacity	Pearson Correlation	**0.476****	**0.507****	**0.529****	0.174	**0.482****	**0.374****	**0.377****	**0.522****
	Sig. (2-tailed)	**0.000**	**0.000**	**0.000**	0.169	**0.000**	**0.002**	**0.002**	**0.000**
	N	**64**	**64**	**64**	64	**64**	**64**	**64**	**64**
Technical (Physical) Resources	Pearson Correlation	**0.348****	0.169	**0.559****	0.214	0.093	0.136	0.158	0.132
	Sig. (2-tailed)	**0.005**	0.183	**0.000**	0.089	0.464	0.285	0.212	0.298
	N	**64**	64	**64**	64	64	64	64	64
Specific BIM Modelling Capacity	Pearson Correlation	**0.273***	**0.361****	**0.267***	0.095	**0.318***	**0.335****	**0.326****	**0.247***
	Sig. (2-tailed)	**0.029**	**0.003**	**0.033**	0.456	**0.011**	**0.007**	**0.008**	**0.049**
	N	**64**	**64**	**64**	64	**64**	**64**	**64**	**64**
Proposed Methodology	Pearson Correlation	**0.509****	0.092	**0.469****	**0.475****	**0.315***	0.105	0.085	0.040
	Sig. (2-tailed)	**0.000**	0.472	**0.000**	**0.000**	**0.011**	0.408	0.502	0.755
	N	**64**	64	**64**	**64**	**64**	64	64	64
Reputation	Pearson Correlation	**0.266***	0.193	**0.423****	0.103	0.139	0.064	0.051	**0.362****
	Sig. (2-tailed)	**0.034**	0.127	**0.001**	0.418	0.274	0.614	0.688	**0.003**
	N	**64**	64	**64**	64	64	64	64	**64**
Technology Readiness	Pearson Correlation	**0.348****	0.169	**0.559****	0.214	0.093	0.136	0.158	0.132
	Sig. (2-tailed)	**0.005**	0.183	**0.000**	0.089	0.464	0.285	0.212	0.298
	N	**64**	64	**64**	64	64	64	64	64
Organisational Structure	Pearson Correlation	**0.394****	**0.319***	**0.399****	**0.334****	0.245	**0.282***	0.260*	**0.257***
	Sig. (2-tailed)	**0.001**	**0.010**	**0.001**	**0.007**	0.051	**0.024**	0.038	**0.040**
	N	**64**	**64**	**64**	**64**	64	**64**	64	**64**
Cost	Pearson Correlation	**0.283***	0.090	0.144	0.234	**0.325****	0.111	0.017	0.092
	Sig. (2-tailed)	**0.023**	0.481	0.258	0.063	**0.009**	0.381	0.896	0.470
	N	**64**	64	64	64	**64**	64	64	64

** Correlation is significant at the 0.01 level (2-tailed) * Correlation is significant at the 0.05 level (2-tailed). Statistically significant correlations in bold.

Seven of the qualification criteria recorded significant associations with the delivery of BIM within budget with *Administrative and Strategic Capacity* recording the most significant association (r = 0.482; $p < 0.01$) followed by *Staff Experience* (r = 0.404; $p < 0.01$). With regards to the delivery of CSC success through BIM, only four of the qualification criteria recorded significant associations with *Administrative and Strategic Capacity* indicating the most significant correlation (r = 0.507; $p < 0.01$).

In relation to the specific areas of CSC success, all BIM qualification criteria recorded less significant associations overall. *Administrative and Strategic Capacity* emerged with significant correlations across all three areas of CSC success through BIM: (r = 0.374; $p < 0.01$); coordination through BIM had correlation weak but significant coefficients (r = 0.377; $p < 0.01$); and integration through BIM was (r = 0.522; $p < 0.01$).

7.5.4 Relationship between Project Complexity and BIM Delivery Success

Project size did not record any significant relationships with the level of the attainment of success in all the aspects investigated. Furthermore, no aspect of project complexity characteristics affected BIM modelling success (quality, schedule and budget). However, positive significant relationships existed between *Project Supply Chain Complexity* and CSC success through BIM (r = 0.268; $p < 0.05$) as well as coordination through BIM (r = 0.415; $p < 0.01$).

The relationship implies that projects with more complex CSC are more likely to achieve some key SCM objectives through BIM, particularly coordination. *Project BIM Complexity* had significant positive relationship with CSC success through BIM (r = 0.367; $p < 0.01$). This implies that projects on which more complex BIM tasks were required were more likely to deliver success in relation to the attainment of CSC objectives. Projects with high BIM complexity were more likely to deliver BIM within budget though the level of association was weak (r = 0.265; $p < 0.05$). The other success areas with significant and positive relations with BIM complexity was collaboration (r = 0.397; $p < 0.01$) and integration (r = 0.285; $p < 0.05$) of the CSC through BIM. This is presented in Table 7.17.

Despite the establishment of significant levels of association between qualification criteria, project complexity and the attainment of success, the exact causal influence cannot be concluded from correlation analysis. More robust inferential analysis is, therefore, needed in order to establish significant predictive associations between these variables. Linear multiple regression analysis was therefore, adopted to identify the significant predictive capacity of qualification criteria on attainment of success in two areas namely BIM modelling success and CSC success through BIM. The effect of project complexity characteristics on this relationship was also examined.

The correlation matrices did not reveal any significant concerns for multi collinearity (Appendix F4). This is because of recommendations that only high levels of correlation (for example $r \geq 0.9$; $p \leq 0.05$) should provide a basis for concern (Field, 2005).

Table 7.17: Correlation between Project Complexity and BIM Success Indicators

		Project Size	Project Supply Chain Complexity	Project BIM Complexity
Overall BIM Modelling Success	Pearson Correlation Sig. (2-tailed) N	-0.002 0.987 62	0.145 0.259 62	0.169 0.188 62
Overall Supply Chain Success through BIM	Pearson Correlation Sig. (2-tailed) N	-0.033 0.801 62	**0.268*** **0.036** **62**	**0.367**** **0.003** **62**
BIM Delivery Quality	Pearson Correlation Sig. (2-tailed) N	0.052 0.688 62	0.132 0.305 62	0.115 0.375 62
BIM Delivery on Schedule	Pearson Correlation Sig. (2-tailed) N	0.068 0.600 62	0.139 0.283 62	0.046 0.722 62
BIM Delivery Within Budget	Pearson Correlation Sig. (2-tailed) N	-0.126 0.330 62	0.089 0.493 62	**0.265*** **0.037** **62**
Supply Chain Collaboration Through BIM	Pearson Correlation Sig. (2-tailed) N	0.056 0.668 62	0.142 0.271 62	**0.397**** **0.001** **62**
Supply Chain Coordination Through BIM	Pearson Correlation Sig. (2-tailed) N	-0.12 0.354 62	**0.415**** **0.001** **62**	0.228 0.075 62
Supply Chain Integration Through BIM	Pearson Correlation Sig. (2-tailed) N	-0.033 0.798 62	0.142 0.270 62	**0.285*** **0.025** **62**

**Correlation is significant at the 0.01 level (2-tailed) *Correlation is significant at the 0.05 level (2-tailed). Statistically significant correlations in bold.

7.6 THE DEVELOPMENT OF PREDICTIVE MODELS FOR BIM DELIVERY SUCCESS

To identify criteria that influence the attainment of BIM delivery success, multiple regression analysis was applied to all the eleven BIM qualification criteria as predictors of BIM delivery success indicators (outcome variables). Subsequently, two regression models were developed to identify critical criteria that influenced the attainment of BIM modelling success as well as CSC success through BIM on the projects assessed by respondents in the questionnaire survey. The Stepwise procedure was used to identify an optimum regression model. As a result of some missing responses 62 out of the 64 total responses from the survey were included in the regression modelling exercise.

7.6.1 Predictive Regression Model for BIM Modelling Success

A multiple linear regression was calculated to predict overall BIM modelling success. The outcome variable consisted of respondents' assessment of CSC performance in relation to BIM modelling quality, BIM delivery on schedule as well as BIM delivery within budget on a current or recently completed project.

The multiple regression modelling resulted in a statistically significant regression equation was (F [2, 61] = 18.629; $p < 0.05$) with an R^2 of 0.379. R^2 is a measure of correlation and indicates the proportion of the variance in the predictor variable which is accounted for by the model. R^2 is considered a measure of the accuracy or prediction power of the regression model (Field, 2005). Adjusted R^2 is, however, viewed as a more realistic estimate since it takes account of the number of variables in the model as well as number of observations (Brace *et al.,* 2003). Adjusted R^2 of 0.359, implied that the predictors in the regression model account for 35.9% of the variation in the BIM modelling success. Based on an analysis of respondent's performance assessment of CSC firms on the 62 projects analysed, overall BIM modelling success can be predicted from the Equation 7.13:

Equation 7.13: Regression Equation for Predicting BIM Modelling Success

BIM MODELLING SUCCESS = 0.857 +0 .483 (Staff Experience) + 0.447 (Proposed Methodology)

From this regression equation, BIM delivery success on a project increased for every 0.483 units increments in the influence of *Staff Experience* and 0.447 for each unit increment in the influence *Suitable BIM Proposals* submitted by firms prior to commencement of projects. Both *Staff Experience* (p < 0.05) and *Proposed Methodology* (p < 0.05) were significant predictors of overall BIM modelling success.

From this analysis these two dimensions of qualification are the most critical to overall BIM modelling success, specifically the quality of BIM models, the delivery of BIM on schedule as well as within budget. Table 7.18 is a summary of the key parameters of the regression model.

Table 7.18: Regression Analysis Results for BIM Modelling Success

Model Summary							
R	0.616[d]	Std. Error of the Estimate		0.711			
R^2	0.379	Adjusted R^2		0.359			
Durbin-Watson	1.383						
ANOVA							
	df	Sum of Squares		Mean Square	F	Sig.	
Regression	2	18.816		9.408	18.629	0.000[e]	
Residual	61	30.805		0.505			
Total	63	49.621					
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

7.6.1.1 Testing the Assumptions of Regression

Test of Goodness of Fit: In addition to the significant (p < 0.05) regression model and acceptable adjusted R^2 (35.9%), the Durbin-Watson test also recorded value of 1.383 indicating that the residuals errors were not correlated unduly or that there was no significant independence of the error terms. The VIF (variance inflation factor) of predictors was 1.179 for *Staff Experience* and 1.179 for *Proposed*

Methodology are all within acceptable range (1 ≤ VIF ≥ 10) indicative of highly satisfactory results with regard to the non-violation of collinearity assumptions (Kennedy, 1992; Hair *et al.,* 1995).

Residual Analysis: The estimated regression coefficient is based on an assumption that sample points are randomly selected with each coming from identically distributed normal populations. It further assumes that all the data has the same variance. It is recommended that residual analysis be applied to ascertain if the model satisfies this assumption (Field, 2005). To test whether these assumptions were met, an analysis of residuals was undertaken through SPSS v.19. The histogram (Figure 7.3) shows a bell-shaped distribution which is indicative of no violation of the assumptions of normality.

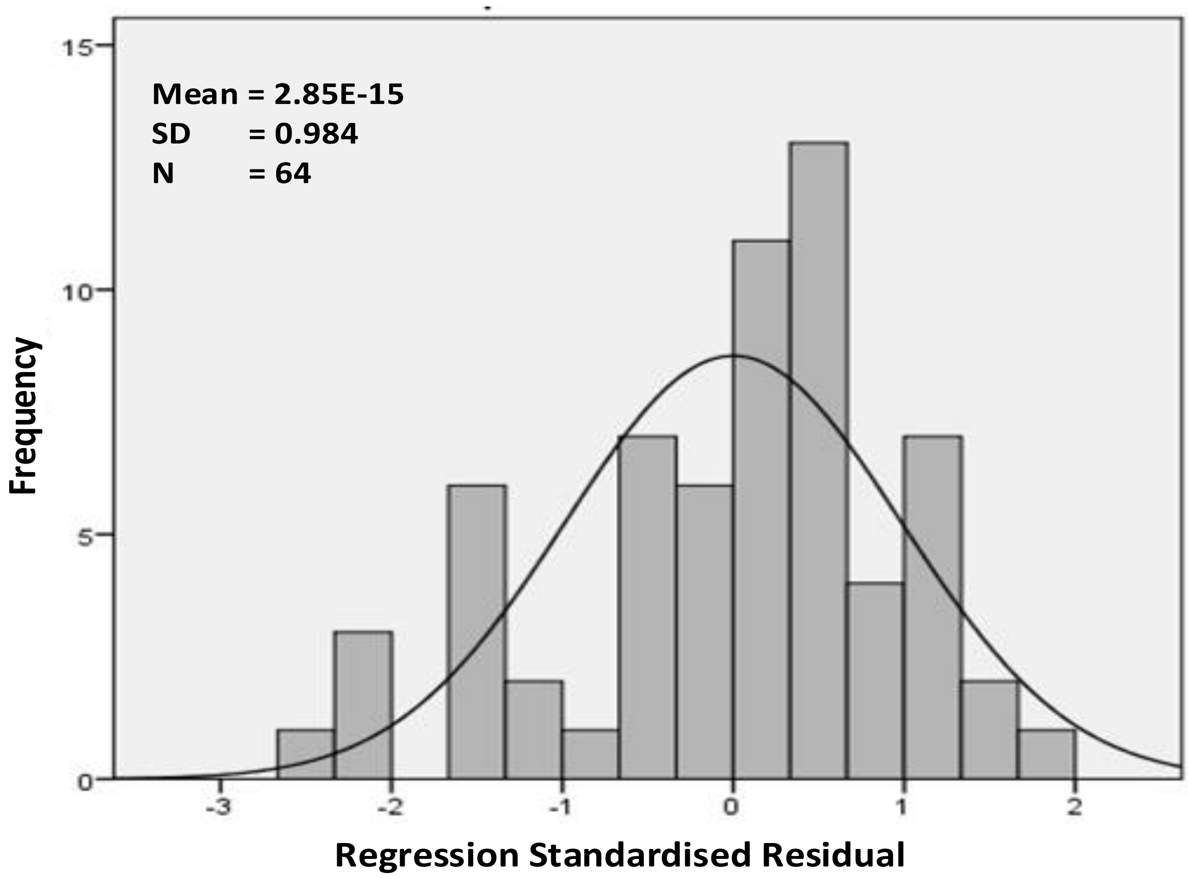


Figure 7.3: Histogram of Standardised Residuals for BIM Modelling Success

The normal probability plot (Figure 7.4) of expected cumulative probability against observed cumulative probability also shows points generally lying close to the straight line. This is indicative of approximately normally distributed data and is consistent with the results from the histogram.

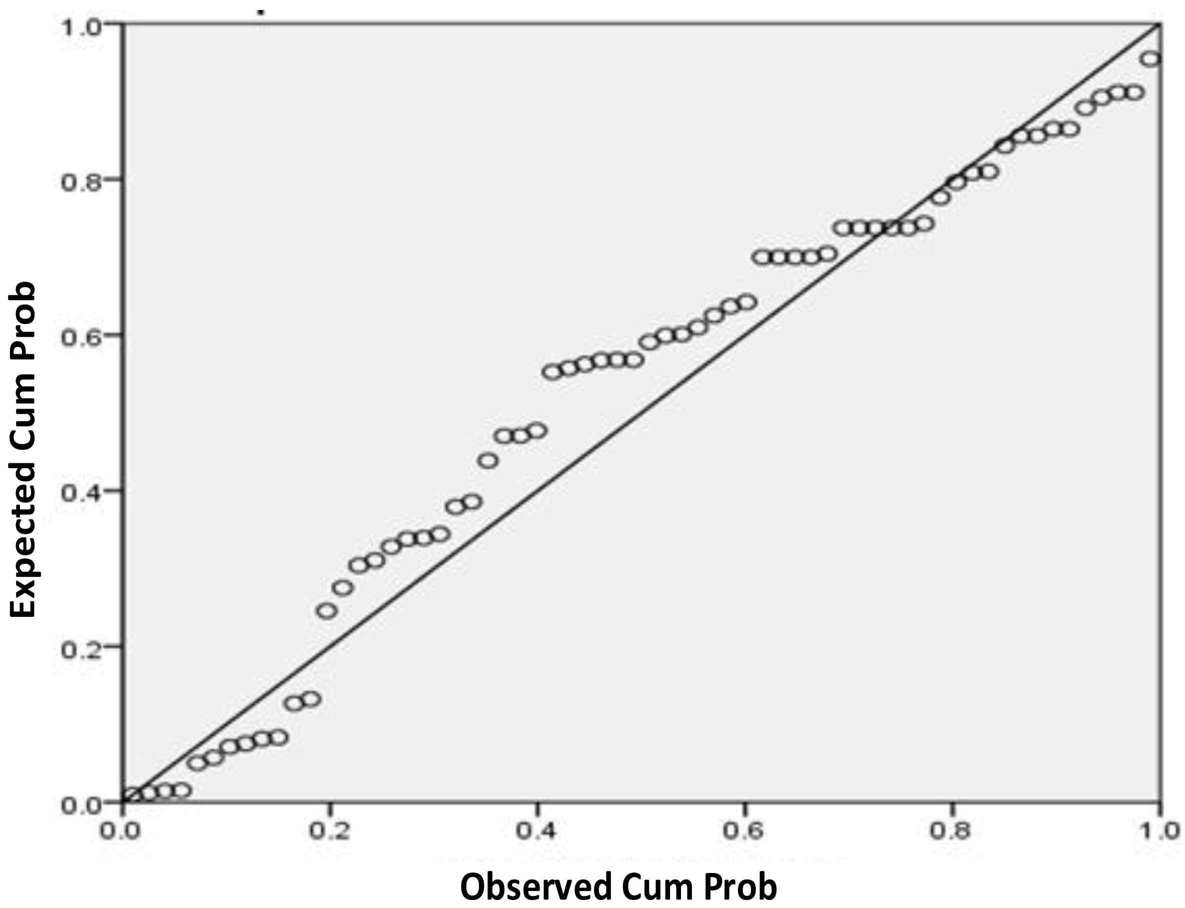


Figure 7.4: Normal P-P Plot of Regression Standardised Residual for BIM Modelling Success

Linearity of the relationship between variables was further tested through an examination of the scatterplot of standardised residual against predicted values of the dependent variable (Figure 7.5). The random distribution of data points is indicative of non-linear relationship. This is evidence that assumptions of linearity of variables were not violated.

The spread of the data point does not show any particular patterns indicative of heteroscedasticity, thus, assumption of constant variance is not violated (see Field, 2005). Overall, the findings from the multiple regression analysis produced valid and accurate predictions having met all necessary assumptions and tests. This is indicative of valid representation of the population as well as adequacy of regression model. As discussed in section 7.5.1.2, these tests are highly necessary in validating the reliability of multiple linear regression models.

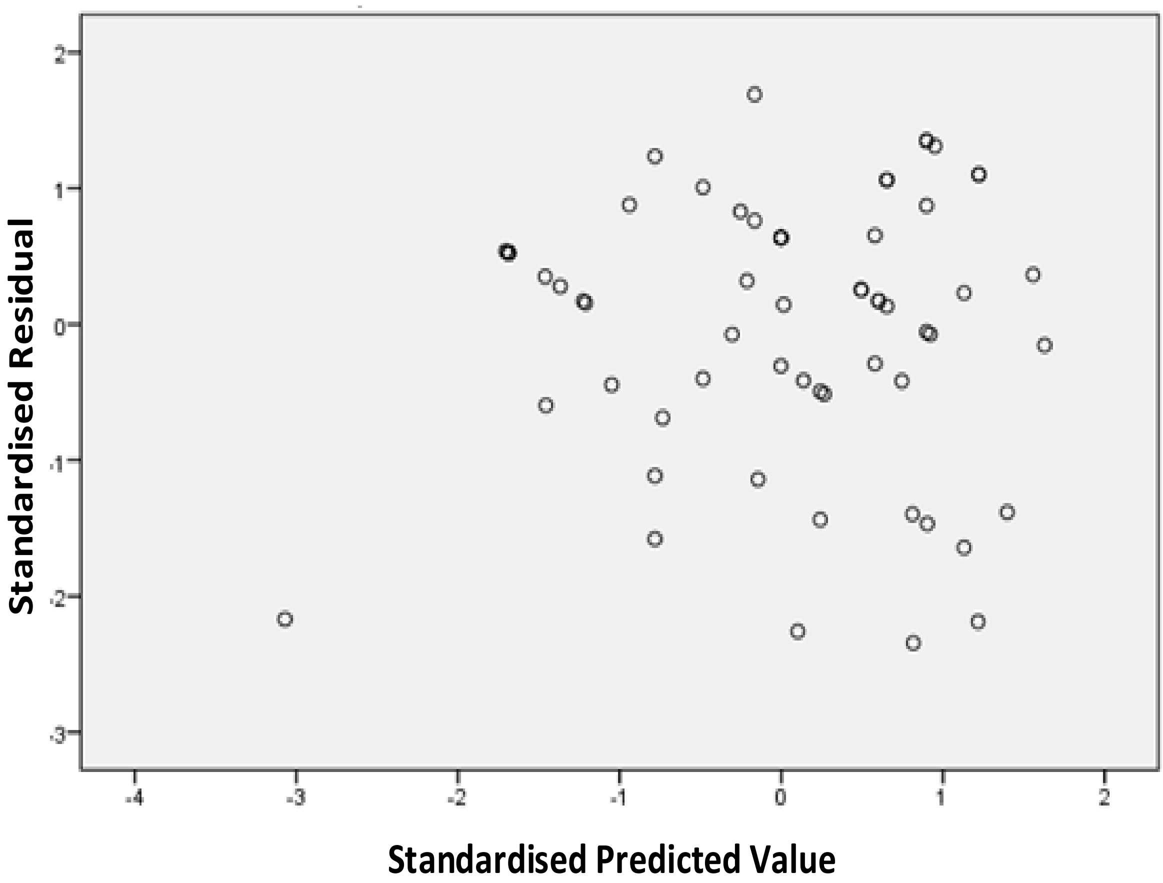


Figure 7.5: Scatterplot-Standardised Residual against Predicted Value (BIM Modelling Success)

7.6.2 Predictive Regression Model for Supply Chain Success through BIM

A multiple linear regression was calculated to predict overall CSC success through BIM. The outcome variable consisted of performance outcomes in relation to collaboration, coordination and integration of the CSC through BIM on the projects assessed. The multiple regression exercise resulted in a significant regression equation (F [1, 62] = 21.489; $p < 0.05$), with an R^2 of 0.257. R^2 is a measure of correlation and indicates the proportion of the variance in the predictor variable which is accounted for by the model.

Adjusted R^2 was 0.245 implying that the predictors in the regression model account for 24.5% of the variation in CSC success through BIM. Based on an analysis of respondents' independent assessment of CSC organisations' performance on 62 projects, overall CSC success through BIM can be predicted from Equation 7.14.

Equation 7.14: Regression Equation for Predicting CSC Success through BIM

OVERALL SUPPLY CHAIN SUCCESS THROUGH BIM = 1.483 + 0.595 (Administrative and Strategic Capacity)

From this regression equation, CSC success through BIM on projects increased for every 0.595 units increments in the levels of influence of an organisation's *Administrative and Strategic Capacity.* This was the only qualification criteria that emerged as significant ($p < 0.05$) predictor of overall CSC success through BIM. From this analysis, administrative and strategy related capacities are the most significant predictors of success in relation to collaboration, coordination and integration of the CSC through BIM on projects. Table 7.19 is a summary of the key parameters of the regression model for predicting CSC success through BIM.

Table 7.19: Regression Results for Overall Supply Chain Success through BIM

Model Summary							
R	0.507[a]	Std. Error of the Estimate		0.781			
R^2	0.257	Adjusted R^2		0.245			
Durbin-Watson	2.059						
ANOVA							
	df	Sum of Squares		Mean Square	F	Sig.	
Regression	1	13.120		13.120	21.489	0.000[b]	
Residual	62	37.855		0.611			
Total	63	50.975					
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

7.6.2.1 Testing the assumptions of regression

Test of Goodness of Fit: The regression model was significant ($p < 0.05$) as well as recorded an acceptable adjusted R^2 value (24.5%), the Durbin-Watson test also recorded a value of 2.059 indicating that the residuals errors were not correlated unduly or there was no independence of the error terms. The Durbin-Watson statistic was computed to test for the independence of the error terms.

The closeness of the value to 2 is indicative of no evidence of first-order autocorrelation. The VIF (variance inflation factor) of the significant predictors was 1, thus, within acceptable range (1 ≤ VIF ≥ 10) (Kennedy, 1992; Hair *et al.,* 1995). This is indicative of highly satisfactory results in relation to the violation of collinearity assumptions.

Residual Analysis: Plots of the residuals are shown in Figures 7.6 and 7.7. These were used to test for any violations of regression assumptions. The histogram (Figure 7.6) shows a bell-shaped distribution which is indicative of no violation of the assumptions of normality. The normal probability plot (Figure 7.7) of expected cumulative probability against observed cumulative probability also shows points generally lying close to the straight line. This is further indicative of approximately normally distributed data and validates the results from the histogram***.***

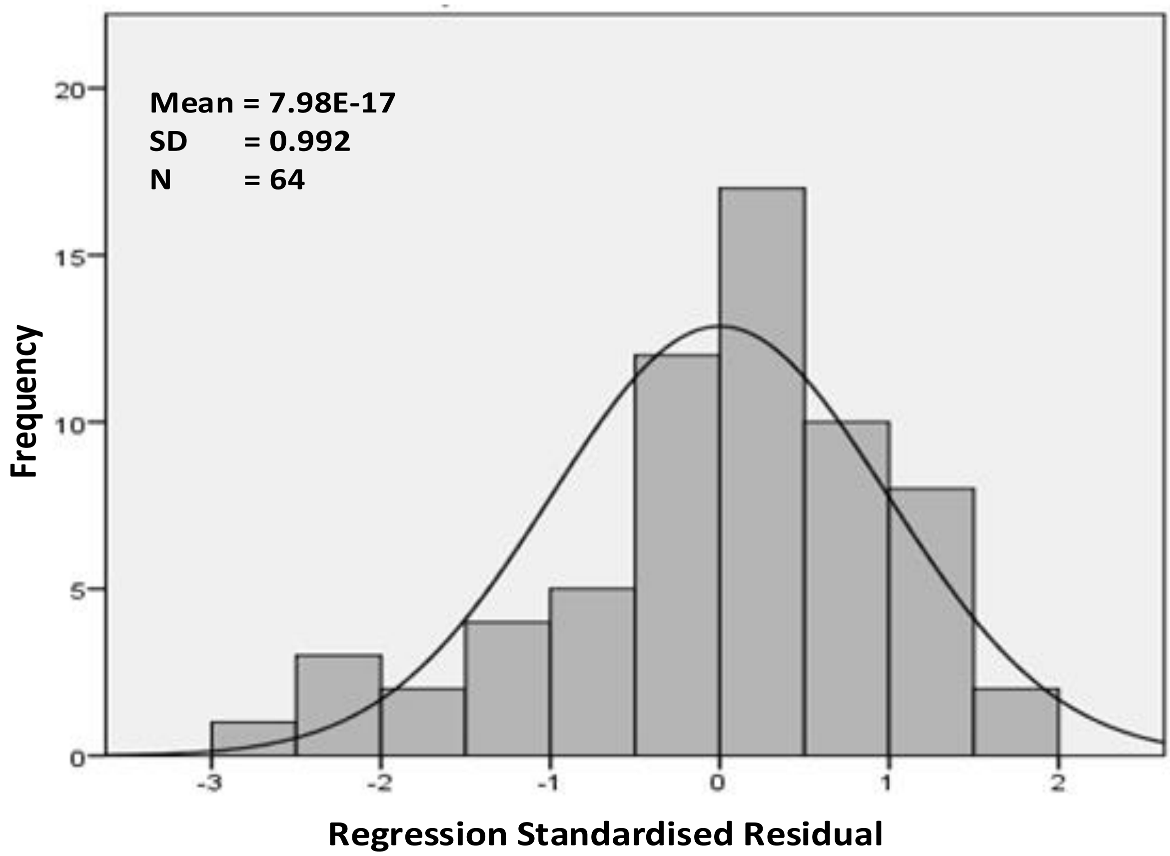


Figure 7.6: Histogram of Standardised Residuals for CSC Success through BIM

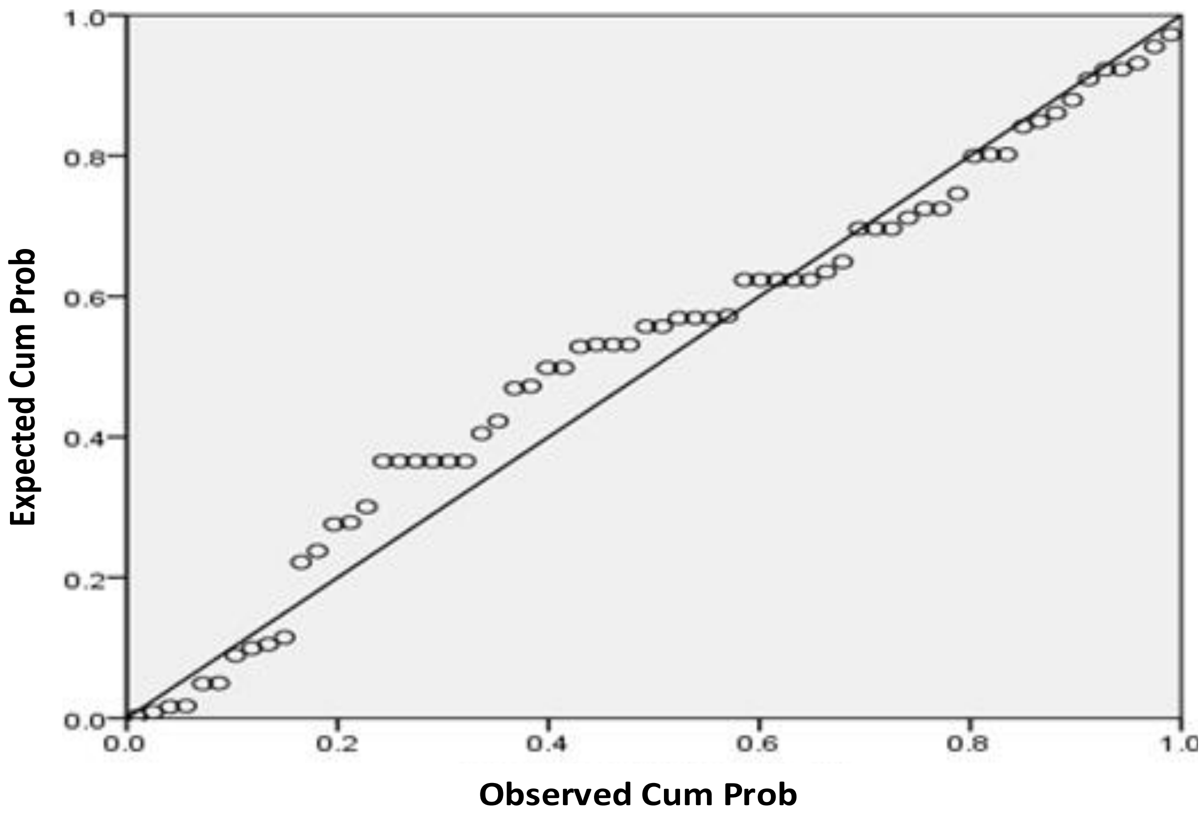


Figure 7.7: Normal P-P Plot of Regression Standardised Residual for CSC Success through BIM

Linearity of the relationship between variables was tested through an examination of the Scatterplot of standardised residuals against predicted values of the dependent variable (Figure 7.8). The random distribution of data points is indicative of non-linear relationship. This is evidence that assumptions of linearity between variables were not violated.

The spread of the data point does not show any particular patterns indicative of heteroscedasticity, thus, assumption of constant variance is not violated (see Field, 2005). Overall, the findings from the multiple regressions met all necessary assumptions from the analysis of the relevant test statistics and residual plots. This is indicative of valid representation of the data. The role of the various tests in validating the reliability of multiple linear regression models has been elaborated in section 7.5.1.2.

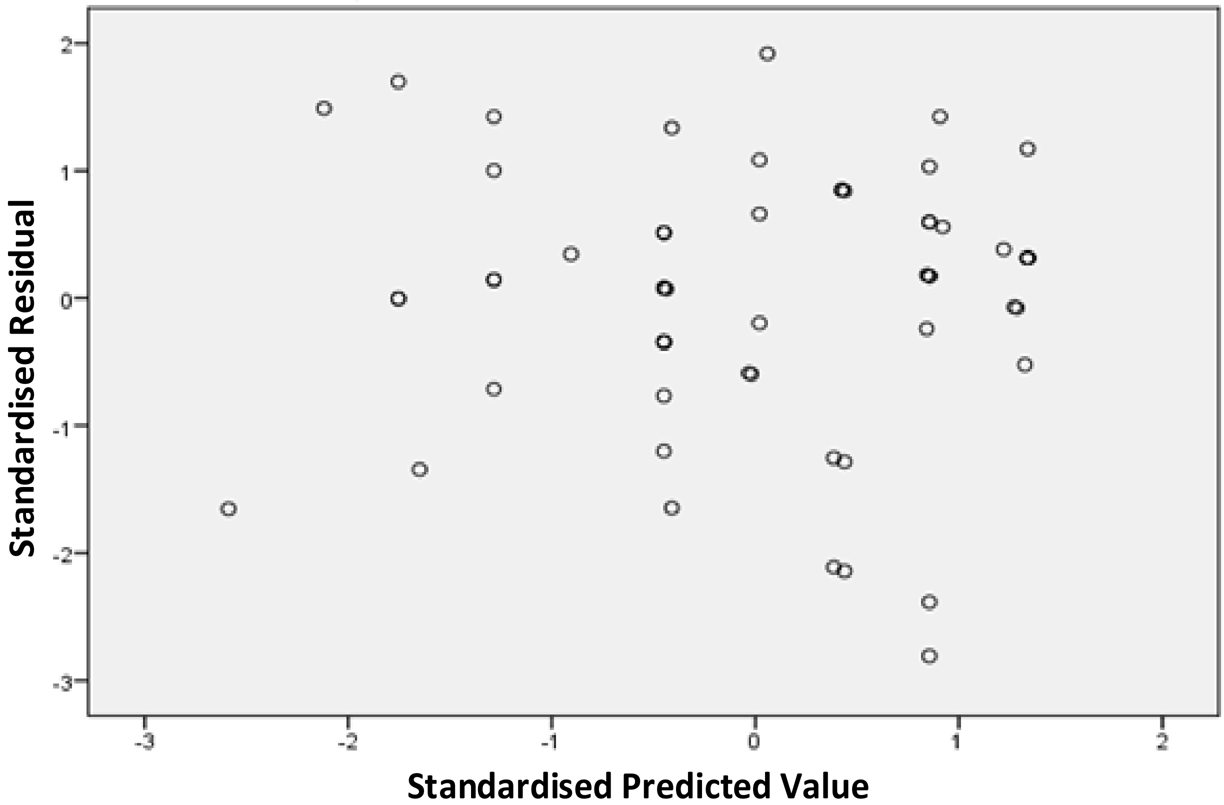


Figure 7.8: Scatterplot-Standardised Residual against Predicted Value (CSC Success through BIM)

7.7 Project Complexity and the Predictive Capacity of Regression Models

From the review of literature, it has been acknowledged that contextual characteristics relating to project complexity may influence the attainment of success (Al-Zahrani, 2013). Similarly, BIM capability can be influenced by BIM complexity (CIC, 2013b). Since the project complexities were graded on identical scales, it was deemed appropriate to assess the relationship between varying degrees of complexity and the attainment of success. The complexity factors are representative of various dimensions of complexity in relation to CSC's BIM use. This was used to create a profile of firms regardless of profession or discipline. 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 project categorised within the following ranges: < £25 million; £26-50 million; £51-75 million; £76-100 million; and > £100 million. 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.

7.7.1 Mediating Influence of Project Complexity on BIM Delivery Success

The two regression models (analysed earlier) were re-run with the inclusion of these project complexity characteristics as additional independent variables. This second-run was to test whether or not any mediating influence existed between the project complexity characteristics and BIM qualification criteria on the other hand. The resulting regression models were then analysed to identify whether or not the original significant predictors remain significant with the addition of mediating variables (additional independent variables).

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, clarifies 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, 2011). In this case, it was tested to identify whether or not project complexity mediated the relationships between qualification criteria and 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 new regression model for BIM modelling success, produced a significant regression model ($p < 0.05$), with marginal increase in the adjusted R^2 (0.368) as compared to the original model (0.359). As shown in Table 7.20, the predictors in the regression equation remained as *Staff Experience* ($\beta = 0.502$; $p < 0.05$) and *Proposed Methodology* ($\beta = 0.446$; $p < 0.05$).

This is indicative of a lack of evidence of any mediating influence of project complexity characteristics on the predictive capacity of the original regression model. Hence variations in the complexity of projects did not unduly affect the influence of qualification attributes on BIM delivery success.

All other test parameters were indicative of a valid model from the examination of test statics and residual analysis which is presented in Appendix F2. An examination of model parameters for the new regression model for overall CSC Success through BIM indicates a significant regression model ($p < 0.05$). There is a marginal decrease in the adjusted R^2 from 0.245 to 0.229 while new significant predictors are now included in the model. As shown in Table 7.21, the significant predictor added to the regression equation is *Project Supply Chain Complexity* ($\beta = 0.423$; $p < 0.05$). *Administrative and Strategic Capacity* ($\beta = 0.754$; $p < 0.05$) remained a strong predictor despite an overall drop in the variance accounted for in the entire regression model.

The results are indicative of a mediating influence of *Project Supply Chain Complexity* in the attainment of CSC success through BIM. Overall, this is indicative of evidence of a mediating influence of *Project Supply Chain Complexity* on the relationship between the predictors and outcome variables. Thus, *Administrative and Strategic Capacity* predicts CSC success through BIM, particularly, on projects with more complex supply chains.

Table 7.20: Comparison of Original and Mediation Regression Models for BIM Modelling Success

	Original Model			**Mediation Model**		
Model Summary						
R	0.616d			0.623b		
R^2	0.379			0.388		
Adjusted R^2	0.359			0.368		
Std. Error of the Estimate	0.711			0.717		
Durbin-Watson	1.383			1.373		
ANOVA						
F	18.629			18.724		
Sig.	0.000e			0.000c		
Variables in Equation						
	β	Sig.	VIF	β	Sig.	VIF
(Constant)	0.857	0.134		0.781	0.180	
Staff Experience	0.483	0.001	1.179	0.502	0.001	1.191
Proposed Methodology	0.447	0.002	1.179	0.446	0.002	1.191

Table 7.21: Comparison of Original and Mediation Regression Models for CSC Success

	Original Model			Mediation Model		
Model Summary						
R	0.507			0.491		
R Square	0.257			0.242		
Adjusted R Square	0.245			0.229		
Std. Error of the Estimate	0.781			0.785		
Durbin-Watson	2.059			2.06		
ANOVA						
F	21.489			11.263		
Sig.	0.000			0.000		
Variables in Equation						
	β	Sig.	VIF	β	Sig.	VIF
(Constant)	1.483	0.001		0.851	0.150	
Administrative and Strategic Capacity	0.595	0.000	1.000	0.754	0.000	1.478
Project Supply Chain Complexity				0.423	0.005	1.009

In other words, the mediation test results are indicative of the fact that projects with more complex supply chains were more likely to achieve collaboration, coordination or integration through BIM. From the new model there is no concrete evidence of variations in the attainment of success across other complexity indicators such as project size or BIM complexity. All other model parameters were indicative of a valid model from the examination of test statics and residual analysis (Appendix F2).

7.7.2 Moderating Influence of Project Complexity on BIM Delivery 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). This is referred to as the interaction between the independent predictor variable and the moderator variable. The relationships between the predictors in the regression models for BIM modelling success and CSC success through BIM was tested through a moderation analysis. This was achieved through PROCESS for SPSS (Hayes, 2016). Using a path analysis framework, PROCESS provides a moderation analysis through an estimation of the coefficients of a regression model (Hayes, 2016). The significance of the interaction is then computed with ($p < 0.05$) and accepted as evidence of moderation. The moderating effect of three dimensions of project complexity were tested on the relationship between each significant predictor and the outcome variables in the regression analysis.

The moderation analysis for BIM modelling delivery success is presented in Table 7.22 consisting of six distinctive interactions. These were the moderating influence of project size, project BIM complexity and project supply chain complexity on the relationships between *Staff Experience, Proposed Methodology* and overall BIM modelling success respectively. None of the interactions, however, recorded significant ($p > 0.05$) levels of interactions.

Table 7.22: Moderating Influence of Complexity Charecteristics on BIM Modelling Success

Outcome: Overall BIM Delivery Success					
Interaction 1(int_1): Staff Experience X Project Size					
R-square increase due to interaction(s):					
	R2-chng	F	df1	df2	sig.
int_1	0 .003	0.137	1.000	58.000	0.713
Interaction 2(int_2): Staff Experience X Project BIM Complexity					
R-square increase due to interaction(s):					
	R2-chng	F	df1	df2	sig.
int_2	0.043	2.949	1.000	58.000	0.091
Interaction 3(int_3): Staff Experience X Project Supply chain Complexity					
R-square increase due to interaction(s):					
	R2-chng	F	df1	df2	sig.
int_3	0 .016	1.530	1.000	58.000	0.221
Interaction 4(int_4): Proposed Methodology X Project Size					
R-square increase due to interaction(s):					
	R2-chng	F	df1	df2	sig.
int_4	0.048	1.553	1.000	58.000	0.218
Interaction 5(int_5): Proposed Methodology X Project BIM Complexity					
R-square increase due to interaction(s):					
	R2-chng	F	df1	df2	sig.
int_5	0.001	0.030	1.000	58.000	0.863
Interaction 6(int_6): Proposed Methodology X Project Supply chain Complexity					
R-square increase due to interaction(s):					
	R2-chng	F	df1	df2	sig.
int_6	0.001	0.047	1.000	58.000	0.829

The moderation analysis for CSC success through BIM is presented in Table 7.23 consisting of three distinctive interactions. These were the moderating influence of project size, project BIM complexity and project supply chain complexity on the relationship between *Administrative and Strategic Capacity* and overall CSC success through BIM respectively. None of the interactions, however, recorded significant ($p > 0.05$) levels of interactions. From this analysis there is no evidence of a significant moderating influence of project complexity characteristics on the relationship between qualification attributes and both dimensions of success. Hence, the attainment of success is not moderated by project complexity.

Table 7.23: Moderating Influence of Complexity Characteristics on Overall Supply Chain Success

Outcome: Overall Supply Chain Success					
Interaction 1(int_1): Administrative and Strategic Capacity X Project Size					
R-square increase due to interaction(s):					
	R2-chng	F	df1	df2	sig.
int_1	0.003	0.123	1.000	58.000	0 .727
Interaction 2(int_2): Administrative and Strategic Capacity X Project BIM Complexity					
R-square increase due to interaction(s):					
	R2-chng	F	df1	df2	sig.
int_2	0.036	1.361	1.000	58.000	0.248
Interaction 3 (int_3): Administrative and Strategic Capacity X Project Supply Chain Complexity					
R-square increase due to interaction(s):					
	R2-chng	F	df1	df2	sig.
int_1	0.008	0.931	1.000	58.000	0.339

7.7.2.1 Relative Contribution of Predictors of BIM Delivery Success from Regression

According to Azen and Budescu's (2003) regression variable importance is contingent on how importance is defined and quantified. For instance, when the stepwise procedure is used there is a natural selection of only relevant predictors (Nathan *et al.,* 2012). Thus, the value of the regression coefficients accurately provide an indication of the relative importance of these predictors (Field, 2005; Nathan *et al.,* 2012). Based on this assertion, the weighted contribution of each significant predictor was computed relative to the summation of regression model coefficients ('B') respectively (Nathan *et al.,* 2012). The weights derived were as follows: *Staff Experience* (51.9%) and *Proposed Methodology* (48.1%) for BIM modelling success; and *Administrative and Strategic Capacity* (64.1%) with the mediation of *Supply Chain Complexity* (35.9%) for CSC success through BIM.

The regression coefficients (β) for the predictors of BIM modelling success (Equation 7.13) as well as the Pearson's correlation coefficients (*r*) depicting relationship between the predictors and each constituent indicator of BIM modelling success is presented in Figure 7.9.

Figure 7.9: Relationships between Predictors of BIM Modelling Success

The regression coefficient (β) for the predictors of CSC success through BIM (Equation 7.14) as well as the Pearson's correlation coefficients (*r*) depicting relationship between the predictor and each of the constituent indicators of BIM modelling success is presented in Figure 7.10. Based on recommended approaches for determination of variable relative importance (Nathans *et al.,* 2012), the weighted contribution of the identified regression predictors and their association with each success indicator is computed based on aggregated regression and correlation coefficients. This is indicated in percentages (%) and brackets in Figures 7.9 and 7.10.

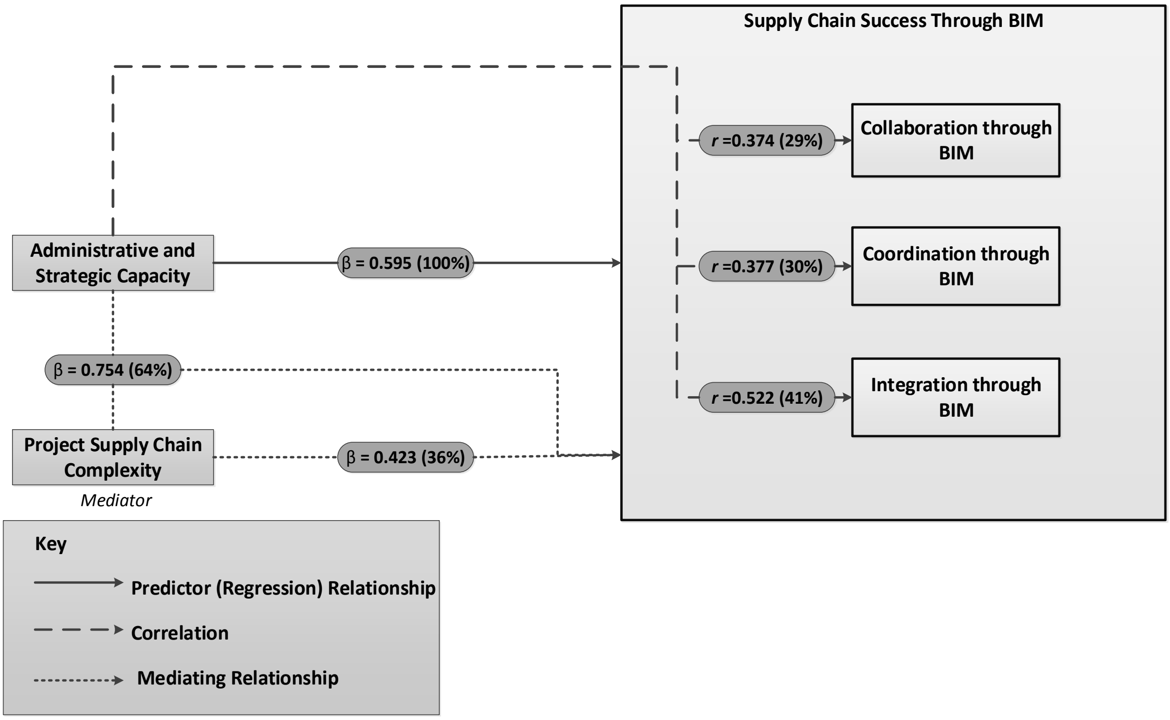


Figure 7.10: Relationships between Predictors of CSC Success through BIM

7.7.3 Overall Regression Model Reliability

The R^2 values (24.2% - 38.8%) recorded in all the regression models are highly significant considering the R^2 values studies employing similar methods within construction management recorded even lower values (4.0% -26.0%) (Omoregie, 2006; Ankrah, 2007). Thus, the models produced in this study explain a highly acceptable and significant level of regression model prediction.

Despite the proposition of having at least 10 observations per predictor in minimum sample size determination in some studies, Harris (1985) stresses out the lack of empirical justification for use of this rule. Similarly, Harris (1985), advances that, reliance on the ratio of number of predictor '*p*' to observations '*N*' is more appropriate for the determination of sample size adequacy in regression analysis. According to Howell (1997), a review of other empirical studies 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. The regression models had 11 predictors while the mediation models had 13 predictors, thus, making the 62 observations used for the regression analysis adequate (11 + 40 = 51 < 62 for main models and

13 + 40 = 53 < 62 for mediation models). Furthermore, this aligns with the number of observations used in studies with similar characteristics (Ankrah, 2007; Ahadzie, 2007).

7.8 INFLUENCE OF ORGANISATION'S CHARACTERISTICS ON BIM DELIVERY SUCCESS

The differences between samples were compared using four main CSC organisational characteristics: CSC type; general experience; CSC organisation's size; and level of BIM task responsibility. ANOVA was, thus, conducted to analyse whether these CSC characteristics could be the basis for statistically differentiating the main findings in the study.

7.8.1.1 Effect of CSC Organisational Type

A one-way ANOVA between-groups was used to analyse the effect of CSC firm type on the attainment of delivery success as well as the level of influence of BIM qualification criteria thereof. From this analysis, firm type had an effect on the perceived level of influence of *Organisational Structure* (F = 2.186; $p < 0.05$) on overall delivery success. This is presented in Table 7.24. No statistically significant relationship was noticed between firm type and the delivery of success in general. However, further cross tabulations were used to assess the descriptive distribution of data in relation to CSC firm types surveyed and the attainment of success.

Table 7.24: Influence of CSC Organisation Type on the Attainment of BIM Delivery Success

ANOVA	Sum of Squares	df	Mean Square	F	Sig.
Professional and Academic Qualifications	6.912	8	0.864	1.571	0.155
Staff Experience	3.769	8	0.471	0.939	0.493
Organisation's Experience	2.674	8	0.334	0.734	0.661
Administrative and Strategic Capacity	4.285	8	0.536	0.892	0.530
Technical (Physical) Resources	8.537	8	1.067	2.089	0.053
Specific BIM Modelling Capacity	4.7	8	0.588	0.771	0.629
Proposed Method of BIM Delivery	6.027	8	0.753	1.367	0.232
Reputation	12.452	8	1.556	1.135	0.355
Technology Readiness	8.537	8	1.067	2.089	0.053
Organisational Structure	18.561	8	2.32	2.186	0.043
Cost	6.786	8	0.848	1.038	0.420
BIM Modelling Success	6.531	8	0.816	1.262	0.282
CSC Success through BIM	10.508	8	1.314	1.981	0.066

From Figure 7.11, it is noticed that *Material and Product Suppliers* and *Architectural – Design Consultants* were the most likely to achieve high rates of success in BIM modelling (quality, schedule, budget). Overall, *Design Consultants* were most likely to achieve BIM modelling success. From the analysis, a significant number of *Engineering Design Consultants* recorded poor levels of success, although, an equally sizeable proportion recorded successful delivery. Thus, *Engineering Design Consultants* reflected the most inconsistent levels in attainment with respect to BIM delivery success.

In relation to CSC success through BIM (Collaboration, coordination and integration), *Material and Product Suppliers* and *Architectural – Design Consultants* were again most likely to achieve high levels of success. *Engineering Design Consultants* were most likely to achieve average or low success rates. This is presented in Figure 7.12. While this provides a good description of the statistical distribution, it remains inconclusive given its descriptive nature and lack of statistically significant results from inferential analysis.

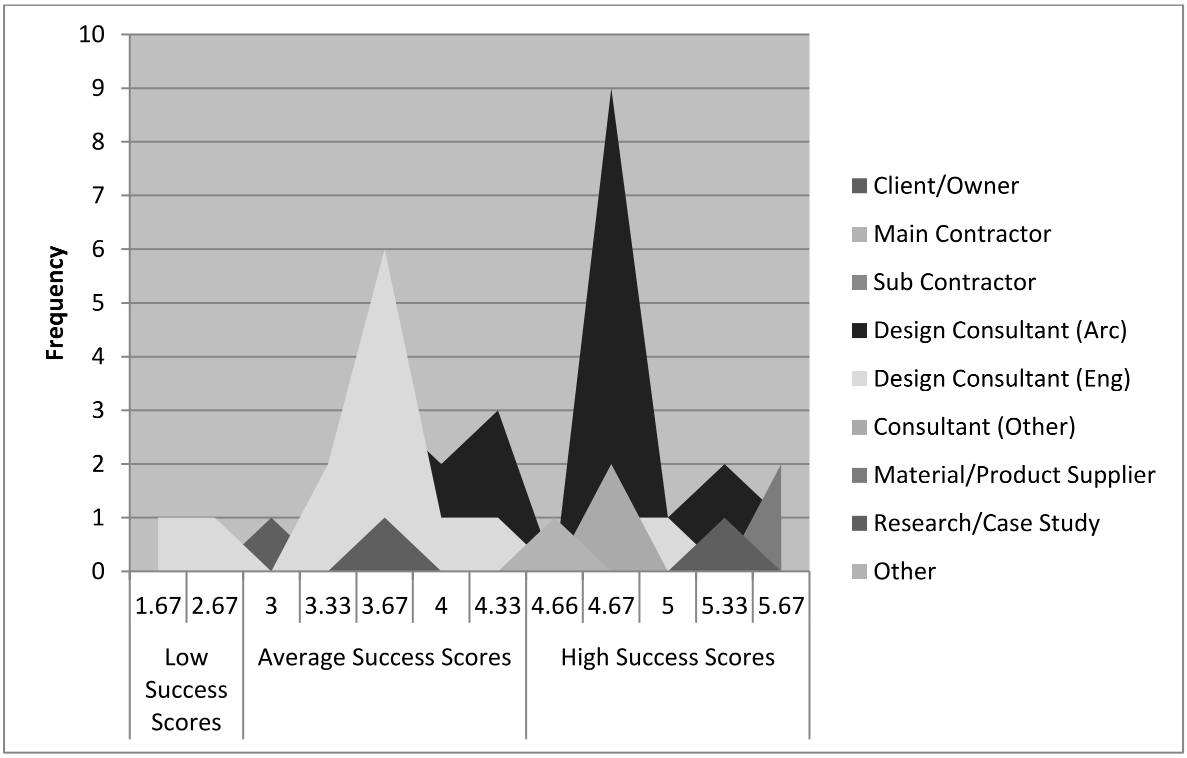


Figure 7.11: Influence of CSC Organisation Type on Attainment BIM Modelling Success

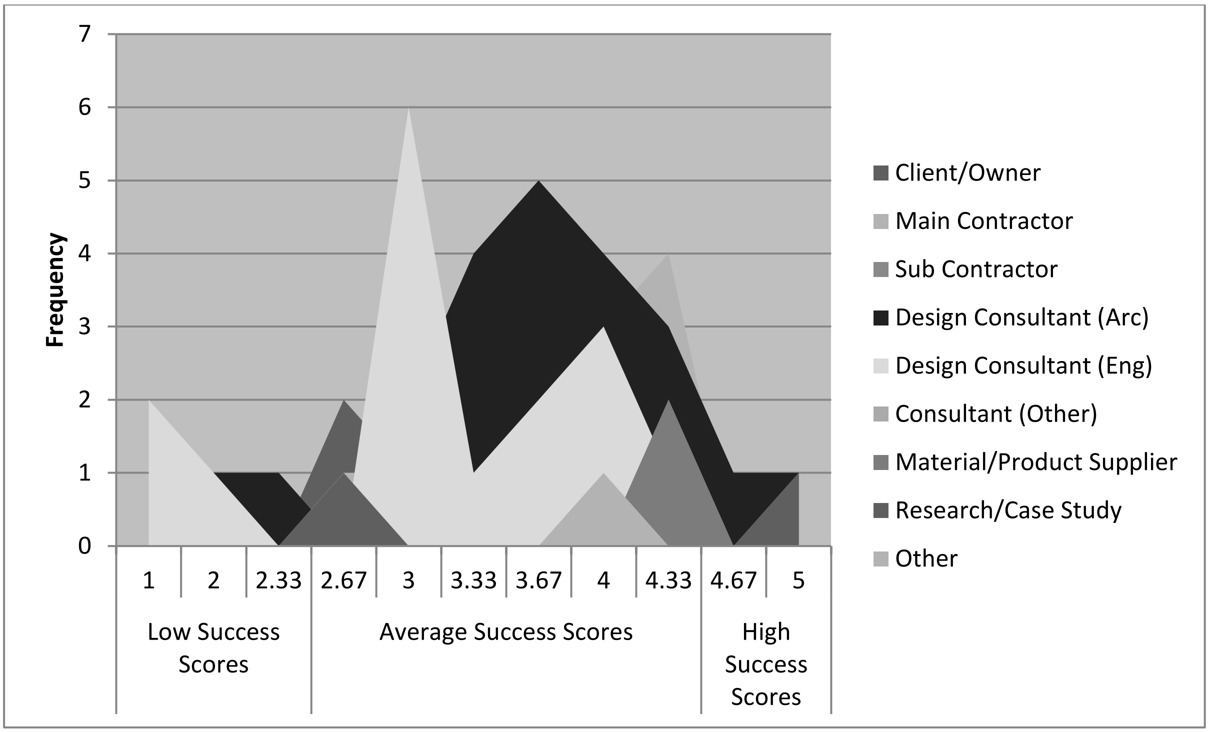


Figure 7.12: Influence of CSC Organisation Type on Attainment CSC Success through BIM

7.8.1.2 Effect of CSC Organisation's Size

From **Table 7.25** CSC firm size demonstrated an effect on the level of attainment of CSC success through BIM ($F = 5.977$; $p < 0.05$) as well as the level of influence of six BIM qualification criteria. These were *Professional and Academic Qualifications*, *Administrative and Strategic Capacity, Technical (Physical) Resources, Proposed Method of BIM Delivery, Reputation* and *Technology Readiness*. A correlation analysis was performed to identify relationship between CSC firm size and these variables. CSC firm size recorded significant but weak correlations with the attainment of CSC success through BIM ($r = 0.284$; $p < 0.05$). This is indicative of the fact that larger organisations were more likely to attain collaboration, coordination and integration through BIM albeit a weak degree of association.

The analysis further revealed significant association between CSC firm size and the level of influence of all BIM qualification criteria except *Reputation* ($r = 0.242$; $p > 0.05$). Hence, the reputation in BIM delivery is independent of organisational size. The highest level of relationship was between CSC firm size and *Proposed Method of BIM Delivery* ($r = 0 .444$; $p < 0.01$). This is presented in Table 7.25.

7.8.1.3 Effect of CSC Organisation's General Experience

The general experience of a CSC firm did not have an effect on the attainment of BIM delivery success *per se*. General experience, however, had an effect on the influence of eight BIM qualification criteria: *Professional and Academic Qualifications; Staff Experience; Organisation's Experience; Administrative and Strategic Capacity; Technical (Physical) Resources; Reputation; Technology Readiness;* and *Organisational Structure*. The correlation analysis between the general experience of a CSC firm, and these variables did not, however, record any significant levels of association. This is presented in Table 7.25.

7.8.1.4 Effect of CSC Organisation's BIM Task Responsibility

The one-way ANOVA between-groups for CSC BIM Task Responsibility in delivery revealed the existence of a significant level of effect on CSC Success through BIM. This is summarised in Table 7.25.

Further test of association revealed that higher levels of BIM task responsibility of a CSC firm was associated with higher levels of attainment of success through BIM (r = 0.443; p < 0.01). With regards to the levels of influence of qualification criteria all the following criteria recorded significant effect of BIM task responsibility on their level of influence of success: *Professional and Academic Qualifications; Organisation's Experience; Administrative and Strategic Capacity; Technical (Physical) Resources; Specific BIM Modelling Capacity; Proposed Method of BIM Delivery; Technology Readiness;* and *Organisational Structure*.

From the correlation tests, all these variables also recorded significant levels of association except *Proposed Method of BIM Delivery* (r = 0.235; p > 0.05). *Organisational Structure* recorded the highest level of association with BIM task responsibility of the CSC (r = 527; p < 0.01).

Table 7.25: Influence of CSC Firm Characteristics on the Attainment of BIM Delivery Success

	Test Variable	ANOVA					Pearson's correlation			
		Sum of Sq.	df	Mean Sq.	F	Sig.	*r*	Sig. (2-tailed)	N	Sig. *r* Rank
CSC Size	Professional and Academic Qualifications	6.316	2	3.158	6.246	0.003	0.386**	0.002	64	2
	Administrative and Strategic Capacity	10.033	2	5.017	11.218	0.000	0.372**	0.002	64	5
	Technical (Physical) Resources	9.281	2	4.641	10.349	0.000	0.384**	0.002	64	3
	Proposed Method of BIM Delivery	7.803	2	3.902	8.34	0.001	0.444**	0.000	64	1
	Reputation	19.311	2	9.655	8.592	0.001	0.242	0.054	64	
	Technology Readiness	9.281	2	4.641	10.349	0.000	0.384**	0.002	64	3
	CSC Success through BIM	7.697	2	3.849	5.977	0.004	0.284*	0.023	64	
CSC General Experience	Professional and Academic Qualifications	6.432	3	2.144	4.187	0.009	0.009	0.945	64	
	Staff Experience	7.682	3	2.561	6.486	0.001	0.003	0.982	64	
	Organisation's Experience	5.986	3	1.995	5.509	0.002	0.159	0.210	64	
	Administrative and Strategic Capacity	5.821	3	1.94	3.697	0.016	0.198	0.116	64	
	Technical (Physical) Resources	13.466	3	4.489	11.624	0.000	0.178	0.158	64	
	Reputation	18.024	3	6.008	5.162	0.003	0.09	0.480	64	
	Technology Readiness	13.466	3	4.489	11.624	0.000	0.178	0.158	64	
	Organisational Structure	11.727	3	3.909	3.597	0.019	-0.045	0.727	64	
CSC BIM Task Responsibility	Professional and Academic Qualifications	11.231	3	3.744	8.443	0.000	0.384**	0.002	62	4
	Organisation's Experience	4.686	3	1.562	4.235	0.009	0.418**	0.001	62	3
	Administrative and Strategic Capacity	5.109	3	1.703	3.157	0.031	0.364**	0.004	62	5
	Technical (Physical) Resources	4.367	3	1.456	3.008	0.037	0.278*	0.028	62	6
	Specific BIM Modelling Capacity	10.609	3	3.536	6.285	0.001	0.438**	0.000	62	2
	Proposed Method of BIM Delivery	8.574	3	2.858	6.137	0.001	0.235	0.066	62	
	Technology Readiness	4.367	3	1.456	3.008	0.037	0.278*	0.028	62	6
	Organisational Structure	27.929	3	9.31	11.381	0.000	0.527**	0.000	62	1
	CSC Success through BIM	9.508	3	3.169	5.162	0.003	0.443**	0.000	62	

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

7.9 SUMMARY OF RESULTS

From the analysis of data from the Delphi surveys, a concise number of eleven critical BIM qualification criteria and 28 sub-criteria had been identified. These criteria cut across distinctive areas of assessment namely competence, capacity and resources, culture and attitude as well as cost. The main BIM qualification criteria are as follows: *Professional and Academic Qualifications; Staff Experience; Organisation Experience; Administrative and Strategic Capacity; Technical (Physical) Resources; Specific BIM Modelling Capacity; Proposed Methodology; Reputation; Technology Readiness; Organisational Structure* and *Cost* of service. From the Delphi Survey *Managerial Staff BIM Experience* and *Network Infrastructure Availability* emerged as the most critical criteria for assessing a CSC firm's suitability for selection.

The survey was used to ascertain criteria contribution to BIM delivery success. From the survey results, *Specific BIM Modelling Capacity* and *Organisation's Experience* were found as the most important contributors to overall BIM delivery success as a whole. In relation to sub-criteria *Key Technical Staff BIM Experience* and *Suitability of Proposed BIM Execution Plans for Project* were the single most important individual contributors to BIM delivery success in general terms.

Survey data was modelled through multiple linear regressions to identify the single most important contributors to the delivery in specific success areas. The first regression model was for BIM modelling success, a criteria measuring the delivery of quality BIM models on time as well as within cost. *Staff Experience* and *Proposed Methodology* were also found to be the most important determinants of BIM modelling success.

A review of the nature of relationship between these significant predictors of BIM modelling success and constituent success indicators is presented based on the Pearson's correlation coefficient values. Based on a comparison of the correlation coefficients, *Staff Experience* recorded 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.

The other regression model was for CSC success through BIM where the attainment of SCM BIM objectives namely collaboration, coordination and integration was assessed. For this category of success, *Administrative and Strategic Capacity* was found to constitute most critical contribution. The extent of attainment of CSC success through BIM, however, depends on the level of CSC complexity.

From the findings, BIM contributes better to CSC collaboration, integration and coordination on projects with complex supply chains. Furthermore, *Administrative and Strategic Capacity* was found as most influential to integration of the CSC through BIM as compared to the attainment of coordination and collaboration through BIM. Furthermore, *Proposed Method* of BIM delivery influences delivery success more as the size a CSC organisation increases. Also, *Organisational Structure* becomes more important contributor to success as BIM task responsibility of a firm increases. Furthermore, the larger CSC organisations as well as CSC organisations with greater BIM task responsibility were identified with slightly higher likelihood of CSC success through BIM.

The findings further showed that criteria such as *Key Technical Staff BIM Experience*, *LOD/LOI Capa*city, *BIM Standards*, *Organisation's BIM Training Arrangements and Data Classification and Naming Practices* are perceived to contribute more to delivery success than the extent of importance placed on them as qualification criteria in practice. Other attributes were found to be considered highly important as qualification criteria but much more than their actual perceived contribution to success in practice. These were *Managerial Staff BIM Experience*, *Internal Use of Collaborative IT Systems Network Infrastructure Availability*, *Reputation of Organisation* and *Extent of IT Support to Core Business and Processes within Firm*.

7.10 CHAPTER SUMMARY

In this chapter the procedure for the quantitative phase of the research has been outlined. The data analysis techniques adopted for the quantitative phase have also been explained together with a presentation of results. The findings provide a basis for the development of a framework to assist decision makers in selecting CSC organisations to be part of BIM-enabled projects. The key findings are discussed in the next chapter together with the development of DSF from the findings.

CHAPTER 8: DISCUSSIONS AND DEVELOPMENT OF DECISION SUPPORT FRAMEWORK

8.1 INTRODUCTION

This chapter contextualises results from the data analysis with reference to literature and empirical studies. Discussions allow deeper exploration of the research findings through a critical synthesis of various segments of the results, as well as comparison with existing knowledge. This provides a reflective understanding of the research problem and how the findings address it. The development of the DSF, based on the research findings is also presented.

8.2 DISCUSSION OF BIM QUALIFICATION IMPORTANCE IN THE SUPPLY CHAIN

Interviews were used to explore the need for assessing CSC firm's ability to work with BIM on projects. The objective was to generate a list of possible criteria that can be adopted as part of qualifying CSC organisations on BIM-enabled projects. This section provides insight into the findings from the interviews.

The interviews highlighted the growing popularity of BIM within the UK, as well as relative lack of BIM use across some segments of the CSC. BIM qualification has become a pre-requisite on most large scale construction projects; consequently, most tender returns in the UK now include some questions relating to CSC BIM capability. This accords with Papadonikolaki *et al.* (2015a) who allude to the fact that BIM qualification of the CSC is gradually becoming part of construction SCM. Results point towards greater willingness among the CSC to learn, despite seeming lack of capability among a majority of CSC firms (Robson, 2014). Additionally, findings revealed that none of the existing BIM capability and maturity frameworks are relied upon for the pre-qualification and selection of CSC for BIM-enabled projects, although many firms are developing bespoke assessment methods. The PAS1192:2 (2013) requires that principal suppliers provide a summary of their CSC BIM capability through the SCCS forms; however, it does not appear that this is common practice yet. The results, further, revealed that there is a general lack of reliance on current protocols, frameworks and toolsets to guide the assessment of BIM capability. Thus, BIM qualification of CSC candidates for projects remains an ad-hoc process in practice. Interviewees also acknowledged that assessments are potentially complex in the CSC context because of variations in the type of organisations within a typical CSC. This finding is consistent with the views of Succar (2010) and Kam *et al.* (2013b) who highlighted the need for neutral and adaptable criteria for BIM assessments to suit many contexts of evaluation.

Ways of assessing ability to deliver BIM objectively were also found to be challenging, as portrayed in the quote below:

> "…..*when it comes to BIM capability people say all of the right things in interviews and form…….they tell you what you want to hear and actually when it comes down to it (the project) they don't quite operate in the way that you thought they would…'* [Interviewee 2].

This underscored the need for the development of a set of criteria that can be objectively assessed as evidence of ability to deliver BIM (Succar, 2010). To this extent, knowledge about the impact of qualification criteria on delivery success is very important in the BIM qualification discourse. This also supports the basic aim of the research as well as studies that have advocated prioritisation of qualification criteria based on their influence on success (Doloi, 2009a). There is, therefore, a need for the unification of concepts of BIM capability assessment and the qualification process (Succar, 2009; Kam *et al.,* 2013), as well as indicators of success in delivery (Mom *et al.,* 2014).

The proposed BIM qualification criteria from the data analysis are discussed in the next section.

8.2.1 Proposed BIM Qualification Criteria

The proposed criteria that have been proposed in the study are generally in agreement with BIM capability criteria in the literature and existing frameworks (Succar, 2009; van Berlo *et al.,* 2012; NIBS, 2012; Kam *et al.,* 2014; Succar *et al.,* 2013; Haron, 2013; Giel and Issa, 2014). Regardless of nomenclature, some of the proposed criteria fit Succar's (2010), classifications of BIM maturity, which is defined as the quality, repeatability and degree of excellence in delivering BIM services. For instance, *Capacity and Resources* was proposed as a category comprising technological process maturity and capacity-related criteria for BIM delivery with a high level of similarity with the process, policy and technological maturity areas proposed by Succar (2010). *Competence* was also proposed as a major area of BIM qualification and consisted of criteria related to knowledge and skills in BIM delivery. This has also been considered as part of Succar's (2010) maturity model, though with less prominence as they were considered as sub competencies within process category. *Culture and Attitude* was also proposed, consisting of soft measures of willingness and enabling culture for technology application. While these have not prominently featured in BIM maturity discourse, some studies on BIM competence (Giel and Issa, 2015), BIM benchmarking and readiness (Sebastian and van Berlo, 2010) have acknowledged their role thus propose similar criteria. Furthermore, Succar *et al.* (2013) categorised individual core competencies of BIM to include personality traits and behaviours.

These findings further highlight the uniqueness of BIM qualification from generic capability concepts in a number of ways. The BIM qualification process takes the view of traditional CSC selection, where both generic and contextual indicators of ability must be considered (Holt, 1998). Thus, a significant number of the proposed BIM qualification criteria were directly related to the specific context within which candidates are to be assessed (namely specific projects or client requirements). These contextual indicators of capability must directly address client or project-specific needs. Existing BIM capability frameworks, however, mainly consider the generic indicators of BIM maturity or competence. The contextual criteria proposed during the interviews included, *Cost of BIM Service*, which has also been acknowledged in the CIC BIM planning guide (CIC, 2013b). The other selection specific criteria included *Proposed Method* for BIM delivery on the project being tendered for, *Staff Availability* for project and *Experience on Similar Projects.* These additional criteria have not been adequately considered in BIM capability assessment in existing frameworks, where the focus has often been on BIM implementation and internal organisational process maturity (Succar, 2010; van Berlo *et al.,* 2012; NIBS, 2012; Kam *et al.,* 2013; Haron, 2013; Giel and Issa, 2014).

Based on the findings, an alternative hierarchal structure of criteria is proposed, with cognisance to its relevance to BIM qualification of CSC candidates for projects. Qualification is often aimed at measuring anecdotes as predictors of success; thus, it requires measurement of various attributes that have a more holistic view of capability. The proposed criteria in this study meet this requirement, since they cut across the different concepts and categories of BIM capability (Giel and Issa, 2013). This includes process, people, product-driven, technology or information-driven criteria (Succar, 2010; Giel and Issa, 2013; Chen *et al.,* 2016). Furthermore, some criteria relates to specified performance in response to project specifications or request for proposals. The level of importance accorded the proposed criteria differs depending on the evaluation context (for BIM implementation, performance management or qualification). While previous frameworks are often biased in terms of the categories of criteria considered, this study highlights the need for more holistic consideration of BIM capability metrics in the pre-qualification, and selection contexts.

8.2.2 Discussion of Competence-Related Criteria

The competence category of BIM qualification criteria focussed mainly on people related measures of capability. Proposed criteria in this dimension included the availability of experienced individuals, organisational experience and professional and academic BIM qualifications, or evidence of certification. Competence is described as one of the most important indicators of the ability to deliver BIM (Succar *et al.,* 2013; Murphy, 2014). Competency is generally described as a combination of skills, abilities and knowledge needed to perform a specific task (NPEC, 2002). In the case of BIM, these are the skills, abilities and knowledge required to perform a BIM-related task (Succar, 2010). In consonance with existing theories and definitions, competence resides both within individuals and within organisations as a collective unit (Succar *et al.,* 2013).

According to Succar *et al.* (2013), the ability to adopt BIM-related processes is dependent on proficiency among staff, as well as its aggregated effect on the entire organisation through collective learning as well as the distribution of roles and responsibilities. Existing BIM frameworks and toolsets (Succar, 2010; van Berlo *et al.,* 2012; CIC, 2013b; Kam *et al.*, 2013b; Succar *et al.,* 2013; Giel and Issa 2015; and Chen *et al.*, 2016) have similarly recognised people centric competency measures as criteria for BIM capability. Existing frameworks, however, tend to look at people competency measures from an internal process maturity perspective (specifically, staffing or human resources management) (Succar, 2010; Sebastian and van Berlo, 2010; Giel and Issa, 2014). These studies have, therefore, not placed adequate emphasis on the '*experience'* aspect of people criteria. According to Succar *et al.* (2013), however, experience is the most reliable indicator of BIM capability through provision verifiable information about past activities that predict future propensity towards success. In most instances, experience related criteria were found as individual's most critical measures for qualification in this study. Experience is regarded as one of the critical indicators of skills and knowledge in the application of BIM. This study recommends the measurement of experience through five dimensions, namely the experience of managerial staff, technical staff, BIM software use, past BIM projects and similar project BIM experience.

Other important competence criteria proposed from the findings are, professional and academic qualifications (certification and licences). These criteria substantiate the existence and sufficiency or level of knowledge and maturity, based on an external independent validation process (Succar *et al.,* 2013). The academic and professional qualifications held by key technical staff as well as an organisation's BIM accreditations and certifications were recommended as important during the pre-qualification or selection of CSC. Furthermore, training was recognised as an important approach to competence development. In view of the fact that BIM is relatively new, the availability of appropriate training regimes within a CSC organisation was recommended as critical BIM qualification criteria. According to interviewees, training provides a certain level of confidence that candidates are willing to update their knowledge and skills as BIM technologies evolve. Similar assertions were made by Kam *et al.* (2013) in their recommendation of criteria for assessing project BIM implementation. Because existing frameworks are often for internal performance assessment of process validation, qualifications such as professional or academic certifications and degrees are seldom relied on as a measure of capability. However, a complete maturity assessment cannot be performed for each prospective CSC candidate during selection. Thus, proof of qualification (such as certifications, degrees and accreditations) is regarded as a critical piece of evidence on BIM capability.

According to Kam *et al.* (2014), BIM projects require the availability of professionals with the right skills set and experience for the operation and use of the related digital technologies. In this light, a show of commitment to deploy adequate numbers of human resources for a project must be assessed independent of the existence of personnel within the organisation. According to the BIM experts interviewed, an organisation might prove the existence of competent personnel but, in some cases, fail to deploy these persons on a project. This is usually as a result of workload or a general lack of commitment. Thus, organisations should provide evidence of the availability of their human resource specifically for projects on which they are being qualified to participate. *'Staff availability'* was, therefore, recommended as a criterion for BIM qualification. An organisation's commitment towards deploying resources, has traditionally been assessed as part of contractor selection through an examination of current workload, in order to ascertain whether or not candidates can cope with deployment of resources (Hatush and Skitmore, 1997).

The proposition of staff experience, organisational experience, professional and academic qualifications align with existing knowledge on BIM capability, as well as construction pre-qualification and selection (Cheung *et al.,* 2002; CIC, 2013b; Kam *et al.,* 2013b). While '*experience'* has not featured prominently as an autonomous criterion in many BIM capability maturity frameworks, it is considered as one of the most important criteria in construction pre-qualification and selection. It aligns with people-related BIM capability criteria descriptions from previous frameworks. The CIC (2012) implementation-planning guide has, however, acknowledged the role of *experience* as identified in this study. Despite this acknowledgement of the importance of *experience* in BIM competency assessment (Succar *et al.,* 2013), existing frameworks have not appropriately made distinctions between different dimensions of experience (that is to say experience of managerial staff, technical staff, BIM software use, past BIM projects, collaborative IT and similar project BIM experience).

In relation to the *Competence* category, criteria eliminated at the Delphi stage of the study were generally considered as too similar to other criteria, which were retained as critical. This included some dimensions of training such as *Staff CPD* and level of *IT Training Budget,* which can, however, be assessed as part of *Technical Staff Qualifications* and *Organisation's Training Arrangements* respectively. Other eliminated criteria included *BIM Management Staff Qualifications* in favour of *Technical Staff Qualification*. According to Succar *et al.* (2013), individual (professional and academic) qualifications in BIM are important for successful delivery, however, emphasis was not placed on which category of qualification is most important. The current study, however, highlights the fact that the qualifications such as certifications and degrees, are more important in relation to technical staff rather than managerial staff. In relation to the importance of management's role in the delivery of success, the findings indicated that managers BIM experience is more important than their possession of academic or professional qualifications and certifications in BIM. The findings, however, concur with other empirical studies that have highlighted top management involvement and support as contributors to BIM success (Giel and Issa, 2014; Mom *et al.,* 2014; Tsai *et al.,* 2014).

8.2.3 Discussion of Capacity and Resources-Related Criteria

Several criteria similar to product, process and product elements of BIM capability were recommended in this category. These are the most commonly used category of criteria in BIM capability assessment (Succar, 2010; Chen *et al.,* 2016). This segment contained the highest number of proposed BIM qualification criteria for the CSC. This category highlights the importance of process, product or technology-centric maturity in CSC organisations, as well as infrastructural support for operating common data environments. Furthermore, the importance of implementation strategy is highlighted in the proposed criteria in this section.

The proposed criteria for assessing available capacity and resources mainly relate to having the appropriate vision and mission for the deployment of digital technologies. According to Giel and Issa (2014), this aids an organisation's ability to plan and develop a course of action for BIM execution. Similarly, the quality of BIM implementation strategy is recommended as a key indicator of capacity to deliver through BIM. According to the CIC (2012) implementation guide, the quality of BIM implementation strategy provides the assurance that the policy and systems within a CSC organisation adequately support BIM usage.

BIM is an innovative digital construction phenomenon. Thus, there is a need for an assurance that organisations are pursuing continuous improvement through research and development (R&D) (Murphy, 2014). R&D is recognised as the first component of the BIM innovation lifecycle (Succar, 2010). The availability of BIM R&D efforts within a firm was identified as important in the qualification of CSC to deliver on BIM projects. According to interviewees, this is as a result of the novelty of BIM and relative lack of established processes. Therefore, it is imperative for CSC organisations to exhibit an ability to develop innovative solutions based on some level of formalised experimentation (explicitly R&D). Thus, when considering a CSC organisation as part of a project, it is important to assess the availability of the recognition and structures that support learning and continuous development through R&D.

Since BIM is essentially a process-based innovation underpinned by technology, its success is highly dependent on the availability of technological infrastructure. BIM capability has, mostly focused on technology or infrastructure requirements in existing frameworks, which have largely evolved based on a hard technological deterministic view of BIM usage (Sackey, 2014). Similarly, the availability of network, data storage infrastructure and software have emerged as important criteria in the evaluation of CSC organisations. The expertise to effectively use these technologies is further regarded as critical to the delivery of BIM outputs. Some of the critical areas relate to the ability to process BIM-related data or deliverables to specifications, as specified in EIRs (Al-Ahbabi and Alshawi, 2015). Chen *et al.* (2016) identified this as the information management element while others have broadly categorised it as process criteria. The capacity-related criteria recommended for BIM qualification have all been cited as fundamental blocks to BIM maturity (Succar, 2009; 2012). For instance the availability of BIM standards has been advocated to streamline data sharing and transfer through common protocols and procedures (Gelder, 2015). This is regarded as the most important approach to eliminating interoperability, which remains the most pervasive BIM challenge (Eastman *et al.,* 2008). The application of industry accepted BIM standards within CSC organisations is, therefore, critical when qualifying CSC to be part of projects. Similarly, their ability to consistently label data and BIM output (data naming and classification practices) is regarded as important (Gelder, 2015). According to interviewees one of the biggest challenges affecting effective data exchange and interpretation is the consistency with which data is labelled in BIM models. Another critical area of BIM expertise is the ability to provide adequate and consistent levels of detail and information (LOD/LOI) in the BIM modelling process (CIC, 2013a). Interviewees regarded the availability of process maturity and procedures that ensure modelling with the right amount of detail and information as critical to qualifying a firm to deliver BIM.

Generally, there is a growing demand for an integrative approach to project stakeholder's communication (Eastman *et al.,* 2008; Murphy, 2014). Furthermore, standardisation is identified as critical to integrated communication and workflows within the CSC, and invariably for the integration of CSC organisations (Vrijhoef, 2011). It is also well documented that issues of stakeholder collaboration and integration are underpinned by seamless communication as well as being crucial to the effective use of BIM in the CSC context (Kiviniemi *et al.*, 2008). This finding, therefore, brings into focus the specific capability areas that facilitate such communication in the CSC context of BIM use (data naming and classification practices to be precise; standards; LOD/LOI expertise as well).

From the findings, the specific level of maturity for which a CSC firm can deliver a BIM output should be distinctly considered as a qualification criterion. According to Succar (2010), there are three progressive stages of BIM maturity representing incremental steps towards fully integrated construction systems. The maturity levels are object-based, model-based or network-based capability respectively (Succar, 2009). Finally, the ability to meet project specific requirements for BIM delivery was identified as a critical BIM qualification criterion. A major recommendation in BIM standards is for the CSC to produce project specific BEP's in response to EIR's from clients or principal suppliers (CIC, 2013a; PAS1192:2, 2013). From the findings, industry players take the view that EIR's requirements and specifications are critical to projects and need to be considered during BIM qualification of the CSC. Furthermore, Al-Ahbabi and Alshawi (2015) have recommended tailored BEPs in order to achieve a timely and cost effective approach to deliver EIRs in view of variations in project characteristics and complexity. Thus, the qualification process needs to mandate the proposition of project specific proposals of how CSC intend to deliver BIM. BEPs are recommended as primary evidence of an organisations ability to deliver BIM on a project from the findings. The suitability of proposed methods have also been acknowledged by CIC (2012) and similarly, Haron (2013) who advocates that organisations must demonstrate this for all their project bids. From the findings, an organisation that has access to BIM vendors for after-sales support, troubleshooting and delivery of bespoke BIM tools is also regarded as a useful capacity indicator for BIM delivery.

The *Capacity and Resources* criteria proposed in this study align with most BIM capability frameworks and tools. This category of criteria (product, process and technology) is the most widely used for the determination of the ability to deliver BIM. These mainly refer to BIM deliverables, model data and physical resources such as technology or infrastructure (van Berlo *et al.,* 2012). Similarly, the majority of qualification criteria proposed in this category of measures aligns with a systems and hard technology deterministic view of BIM capability (Sackey, 2014).

Surprisingly, the eliminated criteria during the Delphi study included *BIM Vision and Mission* in favour of broader organisational *IT Vision and Mission.* This supports assertions that BIM strategy must be viewed as an integral part of an organisation's wider technology integration agenda (CIC, 2013b). However, the extent of investment (or budget) for IT was not found to be important as a qualification criterion, thus, eliminated. Most of the proposed criteria related to hardware were eliminated as uncritical, including: *Hardware* itself, *Hardware state-of-the-art*, and *Model Server Usage*. In addition to potential overlap with retained criteria such as *Network Capacity*, responses from the interviews provided possible reasons. *Hardware* in the context of the study was used to describe mainly personal computing systems such as PC's and workstations. According to interviewees, the extent of availability and affordability of personal computing technology makes the assessment of *Hardware* less important, as compared to larger infrastructure such as *Networks Capacity and* centralised *Data Storage Capacity.* In interviewees' opinions, the ability to use these tools or the software components is more important than the physical presence of especially personal computing equipment.

CSC organisations capability in relation to BIM model uses (namely 3D, 4D or 5D, 6D) was also eliminated as a qualification criterion. Generally, most CSC firms are likely to be users of only one or two dimensions of BIM. According to Succar (2009), a single BIM measure should be neutral enough to measure a wide range of scenarios. For instance, architecture firms should be assessed in relation to 2D or 3D, while QS will be assessed mainly in relation to 5D. Thus, a measure of an ability to deliver at a specified level of BIM maturity is found to be more suitable qualification criteria as compared to BIM model uses (that is 3D, 4D or 5D, 6D) expertise. Frameworks, such as VDC scorecard (Kam *et al.,* 2014; CIFE, 2015), include criteria on model uses (specifically 3D, 4D or 5D, 6D), however, this tool was designed for project performance assessment rather than qualification of CSC for selection purposes.

In relation to *Proposed Methodology* for BIM delivery, Delphi participants preferred that this be assessed in relation to its suitability in meeting EIR's rather than assess the level of innovativeness.

This aligns with the CIC Planning Guide (2012) view of proposal evaluation, where innovation is viewed as a grade in the evaluation of *Method Suitability* rather than a stand-alone criterion.

8.2.4 Discussion of Culture and Attitude Related Criteria

Soft measures of BIM capability have largely been ignored by many existing capability frameworks (Sebastian and van Berlo, 2010). This includes the need for assessing appropriate culture of technology acceptance within an organisation in view of the chronic culture of resistance to change within the construction industry (Adriaanse, 2007). According to Linderoth (2010), future adoption and use of BIM will be shaped by the interplay between both technology and the social contexts of usage. Thus, the assessment of capability must include dimensions of competencies that reflect the social context of usage including the psychological or cultural preparedness of the stakeholder (Mahamadu *et al.*, 2014). Related criteria proposed in conjunction with culture and psychological preparedness were: *Reputation*, *Technology Readiness* and *Organisational Structure*. Similar criteria have been attributed to the success of BIM adoption based on review of technology diffusion and acceptance theories (Adriaanse, 2007; Mahamadu *et al.*, 2014). Existing frameworks have, however, largely ignored this category of measures (Sebastian and van Berlo, 2010).

In a study of qualification criteria for design consultants, Cheung *et al.* (2002) recommended assessing the reputation of a firm as a criterion for ascertaining an organisation's willingness to perform. Despite the promotion of collaborative practices, such as long term relationships in CSC management (Pryke, 2009), the existence of *Previous Relationships with a Principal Supplier* was not considered as an important criterion in BIM qualification as compared to satisfaction by past clients on BIM projects through testimonials and references. From the findings, reputation generally provides more evidence of capability than past relationship with the CSC organisation.

Panuwatwanich and Peansupap (2013) highlighted the need for culture to accommodate the adoption of BIM in view of the reluctance fuelled by misconceptions about associated risk associated with using BIM. Mahamadu *et al.* (2014) referred to this as technology readiness as the psychological and behavioral predisposition towards the use of new or BIM-related technology within the CSC. From the findings, *Technology Readiness* was proposed as a measure of the willingness to engage with BIM or new technology in general. Some of the suggested measures under this category of criteria are *Attitude and Willingness* to use BIM through a demonstration of commitment and an *Awareness of BIM Benefits.* Another measure that has been used for assessing the culture of technology readiness is evidence of extensive technology use for the core processes in an organisation's operation (Mahamadu *et al.*, 2014). According to interviewees, these are often difficult to assess objectively; however, engagement with CSC through interviews and inspection of premises could help evaluators to do qualitative assessments of this dimension of qualification criteria.

Another *culture-related* measure was *Organisational Structure.* This represents the level of decentralisation in an organisational structure and was proposed as a measure of the existence of an open collaborative culture. Such organisational structures have been advocated for integrated construction, including the use of collaborative technologies like BIM (Eastman *et al.,* 2008). Such decentralised structures are also known to support innovation and easier technology diffusion (Rogers, 2003).

Despite their use in technology readiness literature, the *Number of Graduates* and *Youthfulness of Staff* (Hanafizadeh and Ravasan, 2011) were eliminated due to potential measurement challenges and ambiguity. Open ended responses in the Delphi study, were suggestive of a lack of suitability of these criteria despite the accepted notion that younger employees, as well as new graduates, are often more enthusiastic about BIM.

8.2.5 Discussion of Cost as a BIM Qualification Criteria

Cost generally remains the most important selection criterion in construction pre-qualification and selection (Holt, 1998; Plebankiewicz, 2012). According to Holt *et al.* (1994) most traditional construction selection models are based on lowest cost considerations. Furthermore, the cost implications of proposed methodology, as well as lifecycle cost, are a major consideration (Hatush and

Skitmore, 1997). From the findings, cost also remains an important consideration in BIM qualification. Despite an expectation of increases in fees charged by CSC firms to deliver through BIM, this study reveals that in some cases clients may benefit from overall lower fees for BIM services. This is exemplified by the quote below from the interviews (as earlier stated):

> *"For a contractor, they would generally put a cost on top to get a BIM manager which obviously will affect architect and M&E engineer's fees, so obviously there is a cost from that end….. from QS point, it saves us time so the client will benefit from our fees being lower …at the moment and shows how competitive the market is because we are able to do a lot of things a lot quicker"* [Interviewee 5].

The proposition of cost aligns with the CIC's BIM implementation guide for evaluation of proposals (CIC, 2013b). Furthermore, process quality including BIM use was found as superior to price considerations in the selection of CSC for BIM projects in Netherlands (Papadonikolaki *et al.,* 2015a). However, cost has hardly been considered in previous capability frameworks since they mostly aimed towards generic BIM capability for the purposes of implementation or performance management.

8.2.6 The most Critical BIM Qualification Criteria

From the findings, the most important BIM qualification criteria were identified as *Organisations BIM experience, Technical (Physical) Resources* and *Professional and Academic BIM Qualifications*. *Managerial Staff BIM Experience, Network Infrastructure Availability* and *Internal Use of Collaborative IT Systems were identified* as the individual most important sub-criteria. From the findings, physical technological infrastructure is regarded as generally important in the BIM qualification process. Overall, this is consistent with the reliance on technological management factors in determining BIM capability in many of the existing 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. The emergence of organisation's 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 criterion (Hatush and Skitmore, 1997; Doloi, 2009a). Many existing capability frameworks relate to internal implementation and benchmarking, thus they often focus 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 predominantly critical to qualification.

Professional and Academic 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.

These findings are consistent with both BIM capability theories, which have alluded to the importance of historical indicators of competence, (Succar *et al.,* 2013) and 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 scrutinised from the perspective of management's BIM experience. Giel and Issa's (2014) study, however, pertains to owner organisation's BIM competence, thus, significantly different to the CSC context.

8.3 THE CONTRIBUTION OF BIM QUALIFICATION CRITERIA TO DELIVERY SUCCESS

According to Chen *et al.* (2016), there is a need for the quantification of BIM's tangible and intangible benefits and objectives in order to ascertain levels of successful implementation. Furthermore, Kam *et al.* (2014) recommended the need to establish the relationship between BIM maturities of projects on the attainment of project objectives. Despite the acknowledgment of the role of BIM capability on the attainment of success, it is unclear how or which aspects of capability influence various elements of success.

According to Succar (2010), the progression from low to high levels of BIM maturity indicates better control of process variation and invariably better predictability of the attainment of project goals and performance (Succar, 2010). The findings generally supported this assertion, with all qualification criteria perceived as influential on overall BIM delivery success, by the CSC firms, assessed by respondents in this study. The success factors investigated in this study were mainly in relation to the delivery of BIM itself, as well as the perceived benefits of BIM to the CSC. The details of the findings are discussed below.

8.3.1 Contribution of BIM Qualification Criteria to Overall BIM Delivery Success

From the findings, the most important contributor to BIM delivery success was the *Capacity and Resources*-related criteria. This category of criteria consists mainly of technology related measures of internal process maturity and availability of infrastructure. *Specific BIM Modelling Capacity* emerged as the single most important criterion in relation to overall delivery success. This finding highlights the importance of internal process maturity in relation to *BIM Standards, Data Classification and Naming Practices, Model Maturity Capacity and LOD/LOI Capacity.* This finding pinpoints the importance of information management related process, as well as, application of related standards including British Standards (BS), PAS 1192-5, UNICLASS, IFC, Construction Operations Building Information Exchange (COBie) as suggested in implementation guidance. While none of the previous studies have specifically looked at the contribution of BIM qualification or capability on BIM delivery success, the findings reveal a high degree of association. Smits *et al.,* (2016) investigated the influence of BIM maturity elements of projects on projects performance, revealing low level of association. Chen *et al.* (2016) identified process and technology as critical to BIM maturity through information management related capabilities of an organisation. Giel and Issa (2014, 2015) on the other hand, identified operational and strategic competencies as the most important determinants of capability. Other frameworks such as the CIC (2012) and VDC scorecard, similarly give high priority to process and technology criteria in the assessment of BIM capability. It is well documented that issues of stakeholder collaboration and integration are underpinned by seamless communication and crucial to the effective use of BIM in CSC context (Kiviniemi *et al.,* 2008). The finding, therefore, brings into focus the specific capability areas that facilitate such communication in the CSC context of BIM use (that is, BIM Standards, Data Classification and Naming Practices, Model Maturity Capacity and LOD/LOI Capacity). Emerging studies on BIM, therefore, advocate a need for greater emphasis on the process related technological maturity as opposed to physical technological factors such as equipment and infrastructure capacity (Husin and Rafi 2013; McGraw-Hill 2009). The findings are therefore consistent with the assertion that process inclined technological factors contribute immensely to BIM delivery success (Chen *et al.*, 2016).

Despite the overall high level of contribution, capacity and resources related criteria, competence related criteria were the most significant individual contributors to delivery success. This mainly related to experience in the delivery of BIM including, *BIM Software Experience, Past BIM Project Experience* and *BIM Experience on Similar Project*. The role of experience is, however, in contrast with most existing studies where process and technology related maturity of organisations are exclusively trusted or dominate criteria used for assessing capability (Succar, 2009; IU, 2009; NIBS, 2012, Kam *et al.,* 2014; Smits *et al.,* 2016).

The study also highlights the importance of BIM-related qualifications (degrees, certificates and licences), since this emerged as the third most significant contributor to delivery success. From the empirical analysis of CSC, organisations with third party certifications on BIM capability as well as qualified staff (educational and professional degrees), were among the most likely to deliver BIM successfully. The finding supports calls for construction organisations and professionals to pursue BIM qualifications and certification. Emerging certifications schemes (for instance BRE, 2016) and academic as well as professional courses in BIM provide an opportunity for evidencing BIM capability as well as establishing pathways for development and sustenance of competency within the CSC (Sacks and Pikas, 2013).

Another finding in this study is the fact that despite the acknowledgement of the contribution 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) framework (Quickscan), which prioritises culture and attitudinal criteria as more important. Despite being recommended by the CIC (2012) BIM implementation guide, the *Cost* of BIM service has not been considered in previous empirical analysis. Thus, no previous studies have investigated the importance of the cost of BIM services relative to other qualification criteria. This study, however, investigated this, with the *Cost* category emerging as the least important contributor to delivery success. 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.,* 1995; Nieto-Morote and Ruz-Vila, 2012). From the findings, higher fees charged did not have a significant effect on the delivery performance of organisations. Therefore, the cost charged by CSC firms does not necessarily indicate the likelihood of success.

This study highlights similarity in the categories of criteria regarded as important indicators of capability (Succar, 2010), as well as predictors of success (Mom *et al.*, 2014). However, deeper analysis revealed that individual sub-criteria importance vary significantly in terms of their perceived importance as qualification metrics as against their perceived contribution to delivery success in practice. While technical physical resources are considered as an important qualification criterion for the CSC, it has been found to contribute less to delivery success. However, technological and administrative process maturity in relation to delivering BIM models, as well as experience and possession of third party certifications on BIM capability, were found to be important qualification criteria as well as critical contributors to delivery success.

8.3.2 Contribution of Criteria to BIM Modelling Success

BIM modelling success was examined to measure attainment of success in three areas namely, BIM quality, BIM delivery within budget, and BIM delivery on schedule. From multiple regression modelling, two out the eleven qualification criteria were found to influence BIM modelling success. These were *Staff Experience and Proposed Methodology.* Further analysis of the nature of the relationship between these two predictors and various constituent elements of BIM modelling success was performed through an examination of the Pearson's correlations. This revealed a higher degree of association between *Staff Experience* and BIM quality as well as delivery within budget. On the other hand *Proposed Methodology* was more associated with delivery on schedule as compared to *Staff Experience.* This is indicative of a high level of association between Individual competencies and modelling quality as well as delivery within budget while execution planning adequacy influenced timely delivery.

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 as well as appropriate execution planning, are found to constitute the most critical capability attributes that influenced successful delivery of BIM in the opinion of respondents.

In so far as the traditional view of success (quality, schedule and budget) is concerned, individual competencies are crucial towards delivery success. According to Succar *et al.* (2013), BIM skills represent procedural or applied knowledge for the delivery of performance. Experience is cited as one of the key indicators of competencies in BIM. While there are multiple areas of performance, Succar *et al.* (2013) has 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 finding can, 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.

While planning has always been recommended for the attainment of project objectives, no empirical studies have explicitly investigated the impact BIM execution plans on successful delivery on projects. However, from the findings the ability to develop and an effective plan or method in response of project needs is identified as key to BIM modelling success, more specifically delivery within schedule. Standards documents such as the CIC protocol (CIC, 2013a), CPIx (2013) and PAS1192:2 (2013) have promoted the concept of BEP. Other studies have highlighted the importance of BEP's to project success (Al-Ahbabi and Alshawi, 2015). However, no studies have sort to establish the relationship between proposed methodology (project specific BEP's) and delivery success in practice from the empirical assessment of data on CSC firm BIM usage. From the findings suitable *Proposed Methodology* 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). On the other hand the delivery of quality BIM models within budget is mostly associated with staff experience. This also aligns with the views that construction organisations are able to conform to requirements better when workforce possess 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 guarantee value as well as more effective delivery of BIM (Succar *et al.,* 2013). Furthermore, staff expertise and proposed methodology have featured among the most important predictors of success in construction studies in general (Doloi, 2009a).

8.3.3 Contribution of Criteria to Supply Chain Success through BIM

From the literature review (*Section 4.3.5*), collaboration, coordination and integration were revealed as the primary objectives of effective BIM use in the CSC. The impact of qualification criteria on their attainment was investigated revealing *Administrative and Strategic Capacity* as the single most important influencer of CSC success through BIM. While other studies have highlighted strategic factors as important to BIM capability overall (Murphy, 2014; Giel and Issa, 2015), this study indicates that, 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. Thus, 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 on 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 (Giel and Issa, 2015). Similarly, the following factors were considered as most important to administrative and strategic capacity: *IT Vision and Mission*, *Quality of BIM Implementation Strategy* and *BIM Research and Development*. While it is still not clear the extent to which the construction industry is leveraging BIM to achieve CSC objectives, this study highlights the importance of strategy and administrative issues on attaining these objectives. The findings suggest that strategic objectives of SCM management must be incorporated in the long term planning activities as well as allocation of resources in BIM implementation in order to attain success. According to Papadonikolaki *et al.* (2015a), CSC BIM performance is underpinned by strategy 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. When organisations are being qualified for projects there must be the recognition that strategic and administrative maturities in BIM are the primary indicators of their likelihood to engage in integration, coordination and collaboration with the rest of the CSC through BIM.

Evidence of BIM R&D within an organisation is a likely indicator of ability to leverage BIM for the attainment of SCS objectives (Succar, 2010). The findings, therefore, support these assertions and highlight the fact that the attainment of CSC objectives through BIM are not dependent on procedural, process, or technology related capacity. This suggests that management and strategic level factors influence the attainment of indirect benefits, such as collaboration, coordination and integration. This finding is consistent with the assertions 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 aligns with existing evidence that CSC and SCM objectives are not solely met by the use of technologies like BIM but also other physical interactions (Cerovsek, 2011), as well as cultural and commercial imperatives (Vrijhoef, 2011). Furthermore, the effect of BIM capability on delivery success was more pronounced on BIM modelling quality, delivery of BIM on schedule and within budget. These indicators can be considered as direct and tangible success measures. The relatively lower levels of statistical association between BIM capability and broader CSC objectives such as collaboration, integration and coordination is consistent within findings from Smits *et al.,* (2016) where BIM maturity was found to influence project level success indicators to a very minimal extent. Thus there must be cautious optimism regarding the expectation that BIM will necessary influence wider project performance expectations.

Most other studies on BIM SCM integration have highlighted the importance of existing relationships between CSC members on BIM success in general (Vrijhoef, 2011; Papadonikolaki *et al.*, 2015a). However, this study did not support this notion, given the fact that none of the criteria assessing the role of prior CSC relations between parties was not found to be important both as BIM qualification metric and in terms of its contribution to BIM delivery success.

8.3.4 The Influence of Project and Organisational Characteristics

It is generally accepted that project scenario and characteristics may affect the attainment of success (Tatari, 2009; Al-Zahrani and Emsley, 2013; Al-Ahbabi and Alshawi, 2015). In this study, there was evidence of some marginal effects of project or CSC organisational characteristics on the attainment of success, as well as the interactions between qualification criteria. Firstly, it was found that the attainment of CSC success through BIM was mediated by project CSC complexity. Complex supply chain refers to projects with multi-level CSC with several interactions where most of the CSC tiers are required to produce some level BIM compliant data or deliverables. This supports the view in the literature that, as CSCs become complex, there is a need for the use of collaborative technologies to ensure more effective and efficient management of information (Pryke, 2009; Mahamadu *et al.,* 2013a; Mahamadu *et al.,* 2014). Thus, the findings suggest that the use of BIM to leverage SCM objectives has more value in complex CSC scenarios. According to Vrijhoef (2011), the level of complexity of a CSC determines the levels of technology required to achieve SCM objectives such as collaboration, coordination and integration.

With regards to CSC organisation's characteristics, *Material and Product Suppliers* and *Architectural Design Consultants* were found to be the most likely to achieve desirable levels of success in BIM modelling (quality, schedule and budget). Despite acceptable rates of success among most of the *Engineering Design Consultants*, they were also the most likely to record low levels of success. Although, the population of material suppliers surveyed was limited, this finding suggests that material suppliers who commit to deliver BIM are likely to succeed in relation to quality as well as delivery on time and within budget. This success could also be as a result of relatively lower levels of task responsibility since materials suppliers are less likelihood to be required to deliver a large amount of BIM output. Architectural practices have often been identified as leaders in the use of BIM as compared to other trades in the CSC (McGraw-Hill, 2009; McGraw-Hill, 2012). Thus, they are most likely to be experienced in the use of BIM. This concurs with the research findings about the importance of experience in BIM delivery success.

Most of the other CSC organisational characteristics investigated did not have an impact on the attainment of success *per se* but rather affected the level of influence of qualification criteria. This included organisation's size and level of BIM task responsibility. Though relatively low levels of influence was noticed, it was clear that *Proposed Methodology* influenced delivery success more within larger CSC organisations. This finding supports the notion that BIM execution planning is more important to larger organisations' operations than smaller organisations (Eastman *et al.,* 2008). Furthermore, when BIM task responsibility increases there is a need for more decentralisation in organisational structures. This also supports the view in the literature that, open and effective communications is key to BIM success in general (Dossick and Neff, 2010). Furthermore, the more complex an organisation's BIM responsibility, the more the need for open and decentralised organisational structures to support the BIM process.

8.3.5 BIM Capability and Delivery Success

Despite the emergence of studies on BIM capability no existing studies have sought to identify practical and theoretical relationships between BIM capability and BIM delivery success. Research by Chen *et al.* (2014) and Chen *et al*. (2016) have provided some empirically supported insights on the relationships between capability criteria, their interrelationships and contribution to BIM maturity development. Maturity, however, broadly refers to the presence of the ability and the consistency with which this ability can be demonstrated. While by inference, the availability of BIM maturity is indicative of a likelihood of success, the possession of maturity alone cannot be accepted as success in the delivery of BIM (Chen *et al.,* 2016). Smits *et al.,* (2016) study of Dutch AEC firms revealed a lack of significant correlation between an organisation's BIM maturity and their project performance. However since the study by Smits *et al.* (2016) did not consider the performance in relation to the delivery of BIM itself, the current findings provide significant insight into this relationship (between BIM capability and specific BIM delivery success criteria. The findings show that BIM capability attributes contribute significantly to delivery success as well as CSC induced performance through BIM.

The findings show that technology-related process maturity for BIM modelling as well as knowledge and skills in modelling acquired from experience, are adequate indicators of capability and likelihood of successful delivery. Thus, the relationship between the possession of a capability to deliver BIM and the likelihood of delivering it successfully has been empirically established. The finding broadly supports the notion that capability factors are usually the CSFs in BIM implementation (Mom *et al.,* 2014; Tsai *et al.,* 2014). Infrastructural support for BIM processes has been identified as the primary differentiator in the application of BIM skills and competencies (Chen *et al.*, 2014; Tsai *et al.,* 2014). However, this study shows that, while this support can be regarded as a key indicator of BIM capability, the same support contributes less to the attainment of key BIM delivery objectives.

8.3.6 BIM Delivery Success and Qualification of the CSC

The quantification of the impact of selection criteria on success has been recommended to aid more evidenced based pre-qualification and selection, in construction (Doloi *et al.,* 2009a). No studies have explored this phenomenon in the BIM or CSC context. The findings shed light in a number of ways. BIM qualification criteria used within the UK industry are generally modelled around the concept of BIM capability. Thus, similar criteria used for assessing capability, maturity, competence and readiness are used in qualifying CSC firms for projects, though with no recourse to their implications on success. From the findings individual BIM qualification criteria contribute to the various dimensions of delivery success to different extents. Furthermore, while some criteria are perceived as critical to qualifying organisations for BIM projects, they may not be as important to delivery success. Thus, it is important to consider the implications of qualification criteria on various delivery success areas as part of the prioritisation of criteria for selection or pre-qualification. The empirically established relationships between qualification criteria and success is therefore a precursor for the determination of suitable CSC candidates based on their propensity towards various aspects of delivery success.

8.4 DEVELOPMENT OF DECISION SUPPORT FRAMEWORK

Based on the review of the literature, the research findings and discussions, this study adopts a holistic approach towards developing a decision support framework (DSF) for CSC BIM qualification. According to Holt (1998) the decision process for selecting organisations for projects involves the evaluation of performance across different criteria to identify the best (Arslan *et al.*, 2008). This often involves various objective and subjective qualification criteria (Hatush and Skitmore, 1997). It is recommended that DSF's are used to structure the problem in order to aid systematic appraisal (Mohemad *et al.*, 2010). DSF's are not expected to choose the best candidates but rather provide useful information to evaluators about the implications of a candidate's key abilities. The aim of the proposed DSF in this study is to aid evaluators to rank CSC candidates based on their likelihood to succeed. The DSF will further advise on the implications of various BIM qualification attributes in conjunction with delivery success. Thus, the DSF is intended to provide evidence based information to enhance the decision making process. Pre-qualification and selection DSF's in construction should contain the following elements:

- ***A Hierarchical framework of decision criteria*:** this refers to the BIM qualification criteria. In this study, the hierarchy of critical BIM qualification criteria is proposed as the main decision hierarchy. This consists of four distinctive categories of assessment, eleven main criteria and 28 sub-criteria. The development of the hierarchy of BIM qualification criteria is presented in Chapters 6 and 7 and extensively discussed in Chapter 8. The application of the criteria hierarchy to the DSF is explained in *Section 8.4.1* below.
- ***Computational framework:*** Decisions for selection are often based on multiple criteria, thus the determination of the best candidates depends on effective computation and aggregation of performance indices. This often involves the determination of weighted importance of

criteria as well as a summation of performance with respect to each qualification criterion. The weighted importance of criteria in the proposed DSF is based on the quantitative findings in association with their contribution to BIM delivery success. This has been presented in Chapter 7. The remainder of the computational framework for the DSF is discussed in *Section 8.4.2* below. The computational framework also allows the determination of an overall score for each CSC candidate such that they can be ranked in order to determine the best out of a list of alternatives.

- ***Grading and assessment guidance:*** The assessment of performance in relation to each criterion needs to be executed through a scale with corresponding numeric value. The numeric values can then be applied in aggregation of scores for each criterion to derive an overall performance score. A grading guidance is usually applied to aid evaluators in the scoring process. The scales and guidance is discussed in *Section 8.4.3*.

8.4.1 Decision Criteria Hierarchy for the Decision Support Framework

The BIM qualification criteria employed in this study, is presented as the decision hierarchy for the DSF. The decision hierarchy for the DSF is presented in Figure 8.1 with the weighted contribution of each criterion (local weights) to delivery success. Table 8.1, 8.2 and 8.3 contains detailed description of each criteria and recommended approaches for collecting evidence with reference to each criterion.

8.4.2 Computational Structure for the Decision Support Framework

Over the last two decades, there has been greater recognition of the need for the adoption of improved evaluation techniques with respect to selecting organisations for construction projects (Ng, 2001). This has led to the development and proposition of various computational approaches (Abassy *et al.*, 2013). One of the basic approaches that have been proposed for the aggregation of weighted qualification criteria or indices is the dimensional weighting model for the aggregation of weighted ratings from qualification questionnaires (Jaselskis and Russell, 1991).

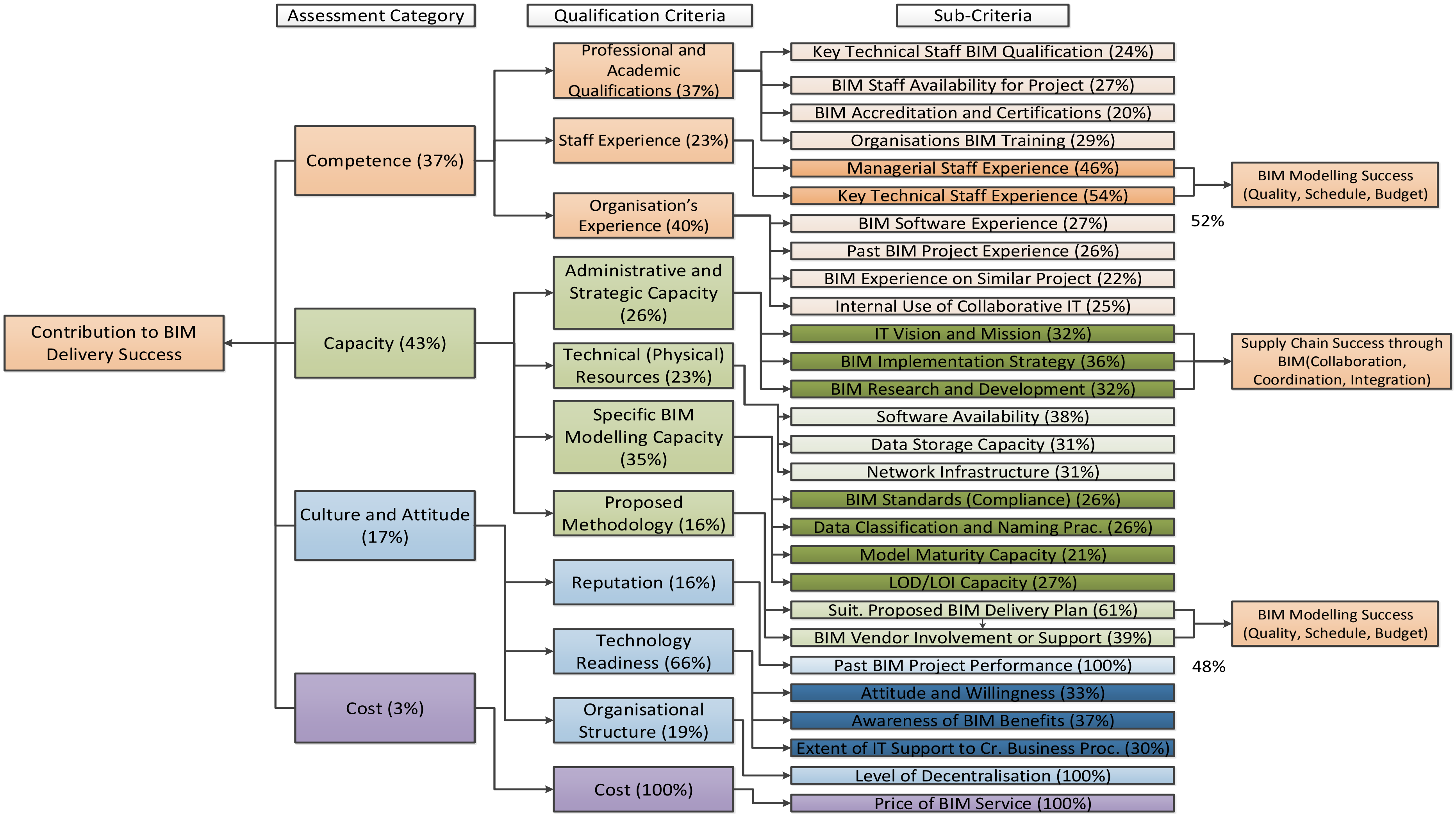


Figure 8.1: Decision Hierarchy of DSF

Table 8.1: Description of Competence Criteria for DSF

BIM Qualification Criteria	Criteria Description	Evidence/ Forms*
Professional and Academic Qualifications: The CSC 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, Certifications, CDP)?	CVs; Certificates; CPIx C1 and B1
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, BRE, BSI and RICS.)?	
Organisation's BIM Training Arrangements	Are there internal training programs and plans that ensure continuous improvement in BIM skills and knowledge?	
Staff Experience: The CSC 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 R&D competencies from past use of BIM)	CVs; Testimonials; CPIx C1
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 CSC organisation demonstrate successful historical use or implementation of BIM?		
BIM Software Experience	Is there evidence of familiarity with requisite BIM software within the firm?	Bespoke RFQ, PQQ Returns; CPIx A1,A3,A4 and B1
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)	

*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).
NB: Rating/Grading Scales provided in Tables 8.4-8.7

Table 8.2: Description of Culture, Attitude and Cost Criteria for DSF

BIM Qualification Criteria	Criteria Description	Evidence/Forms*
Reputation: The CSC 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 A4
Technology Readiness: Is there appropriate culture and attitudes towards BIM?		
Attitude Towards New Technology/Willingness	Has the CSC organisation demonstrated willingness to use innovative technologies including BIM / Is there a culture of readiness for change?	Interviews; Premise visits; CPIx A2, A3 and A5
Awareness of BIM Benefits	Has the CSC 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 Cr Business and Processes within Firm	Has the CSC 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).	Tender Returns

*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). **NB:** Rating/Grading Scales provided in Tables 8.4-8.7

Table 8.3: Description of Capacity and Resources Criteria for DSF

BIM Qualification Criteria	Criteria Description	Evidence/Forms*
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?	Bespoke RFQ, PQQ Returns; Company BEPs; CPIx A5
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 CSC 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?	Bespoke RFQ, PQQ Returns; Company BIM Capability Summaries, Licences; CPIx B1 and B2
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 to can support BIM or centralised data exchange? (e.g. cloud and network bandwidths)	
Specific BIM Modelling Capacity: The CSC 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.)	Bespoke RFQ, PQQ Returns; Company BIM Capability Summaries and BEP, Licences; CPIx A3 and B1
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 Methodology: Is tender response or proposed methodology 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 B1 and B2
BIM Vendor Involvement and Support	Does the CSC organisation have any existing contracts, after-sales and R&D arrangements with BIM/ software/hardware vendors that will benefit project?	

*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).
NB: Rating/Grading Scales provided in Tables 8.4-8.7

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 the experimental knowledge of experts to facilitate evaluation. Holt (1998) reviewed contractor selection modelling methodologies including bespoke approaches, multi-attribute analysis, multi-attribute utility theory, cluster analysis, multiple regression, fuzzy set theory, and multi-variate discriminant analysis. In other studies, Lam *et al.* (2001) applied Neural Networks (NN) to evaluate contractor capability during pre-qualification by matching contractors' attributes to the client's objectives.

Other multi-criteria decision models have relied on the Analytical Hierarchy Process (AHP) as a computational framework (Fong and Choi, 2000; Al-Harbi, 2001; Mahdi *et al.,* 2002). El-Abassy *et al.* (2013) put forward a model based on the integration of Analytical Network Process ANP and Monte Carlo simulation to prioritise highway contractors.

Nguyen (1985) addressed a critical limitation of these models by incorporating Fuzzy Set Theory in the development of a contractor evaluation model. This paved the way for the development of a new generation of models, including Nieto-Morote and 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 on Fuzzy-AHP. The fuzzy set approach allows mathematical modelling of uncertainty and vagueness of the sometimes subjective judgements associated with the evaluation of alternative firms (suppliers) for the purposes of construction or SC management.

These methodologies highlight two critical functions in the decision making process intended for the selection of candidates for projects. These are:

- *Prioritisation of criteria to generate weight (Section 8.4.2.1); and*

  Summation of scores on each criterion to determine overall performance (Section 8.4.2.2).

8.4.2.1 Computation of Weighted Contribution of Criteria

In this study, prioritisation of criteria was performed to generate weightings for their relative contribution to delivery success (as shown in Chapter 7). The weighted mean contribution was adopted to compute criteria contribution to overall delivery success (see Giel and Issa, 2014) as detailed in *Section 7.4.5.1*. Multiple linear regression analysis was then used to identify predictors of success in two key areas, BIM modelling success and CSC success through BIM, as detailed in *Section 7.6*. Holt (1998) recommends multiple linear regressions as a robust approach for predicting best candidates for construction projects. A justification of the analysis techniques adopted for weighting criteria is presented in *Sections 7.4.3 and 7.5.1*. In this study the survey of 64 practitioners on BIM-enabled projects was relied on to generate regression equations and weightings for critical predictors of BIM delivery success. Furthermore, most studies investigating the relationship between qualification criteria and success have similarly relied on the regression analysis of respondent opinions (Doloi, 2009a). The weighted contribution of criteria to various aspects of BIM delivery success has been discussed in *Section 8.3* and summarised in the DSF hierarchy (Figure 8.1).

8.4.2.2 Aggregation of Scores for Prioritising Alternative Candidates

The second step is the computation of overall scores based on performance evaluation of each candidate for each of the criteria. The performance scores for each criterion are aggregated to attain an overall score. The scores are weighted based on the contribution of each criterion to delivery success. Candidates can then be ranked based on their overall weighted scores. The highest weighted score, thus, represents candidates with greatest likelihood of success. Arslan *et al.* (2008) proposed that using complex, computational and mathematical models might not be effective in contractor selection, since evaluators are not familiar with these often complex methodologies. Thus, having already identified the weighted contribution of BIM qualification criteria by means of robust primary research methods, a simple aggregation is recommended for the determination of overall scores (Jaselskis and Russell, 1991). The following formula is adopted for the aggregation of scores (Equation 8.1). Application of the formula (Equation 8.1) to the DSF is exemplified in Figure 8.2, together with a description of criteria weight in relation to their respective influence on various success indicators.

Equation 8.1: Computation of Overall Score for DSF

$$Qualification\ Score = \sum_{i=1}^{n} T_i W_i$$

Where:

Ti = rated qualification criteria, (0≤ Ti≥5), using rating scales (section 8.4.2.3); and

W_i = weighted contribution of criteria to success;

n = number of attributes considered for particular evaluation (i.e. CSC success *n*=1; BIM modelling success *n*=2; and overall *n*=11, *n*=28)

The DSF will, thus, rank firms based on scores representing a prediction of the CSC firm's likelihood to attain success in the following areas: BIM modelling success (quality, schedule and budget); CSC success through BIM (collaboration, coordination and integration); and overall success.

The DSF shows the key criteria required for BIM qualification (Figure 8.2). It summarises the research findings associated with relative contribution of BIM qualification criteria on delivery success (in percentages) based on the relative mean importance, regression (β) and correlation (*r*) coefficients. The framework also shows the project and organisational factors that contribute to variations in criteria contribution and weight (W_i), based on an ANOVA across organisational characteristics and correlation analysis.

8.4.2.3 Scales for Rating Levels of BIM Qualification Criteria

In the pre-qualification or selection process there is always a scale with a corresponding numerical score to aid the evaluation of performance with respect to each criterion. Similarly, this is used in BIM capability assessment where ability is expressed in multilevel graduation (Succar *et al.,* 2013). In BIM assessment maturity, levels are used to indicate progressive levels of capability (NIBS, 2012; Giel and Issa, 2014). The levels indicate the attainment of the goals pertaining to each assessment criterion. Following existing IT capability (SEI, 2002), readiness (Salleh *et al.,* 2010) and BIM capability assessment (Succar 2009; CIC, 2013b) a six point scale is adapted to aid evaluations in the DSF.

Level zero is employed as the lowest point, representing a lack of capacity or performance and level five represents the highest capability or performance. This is used as scales with generic capability level descriptors for the four categories of qualification criteria, following a review of maturity models and the discussions on BIM capability frameworks.

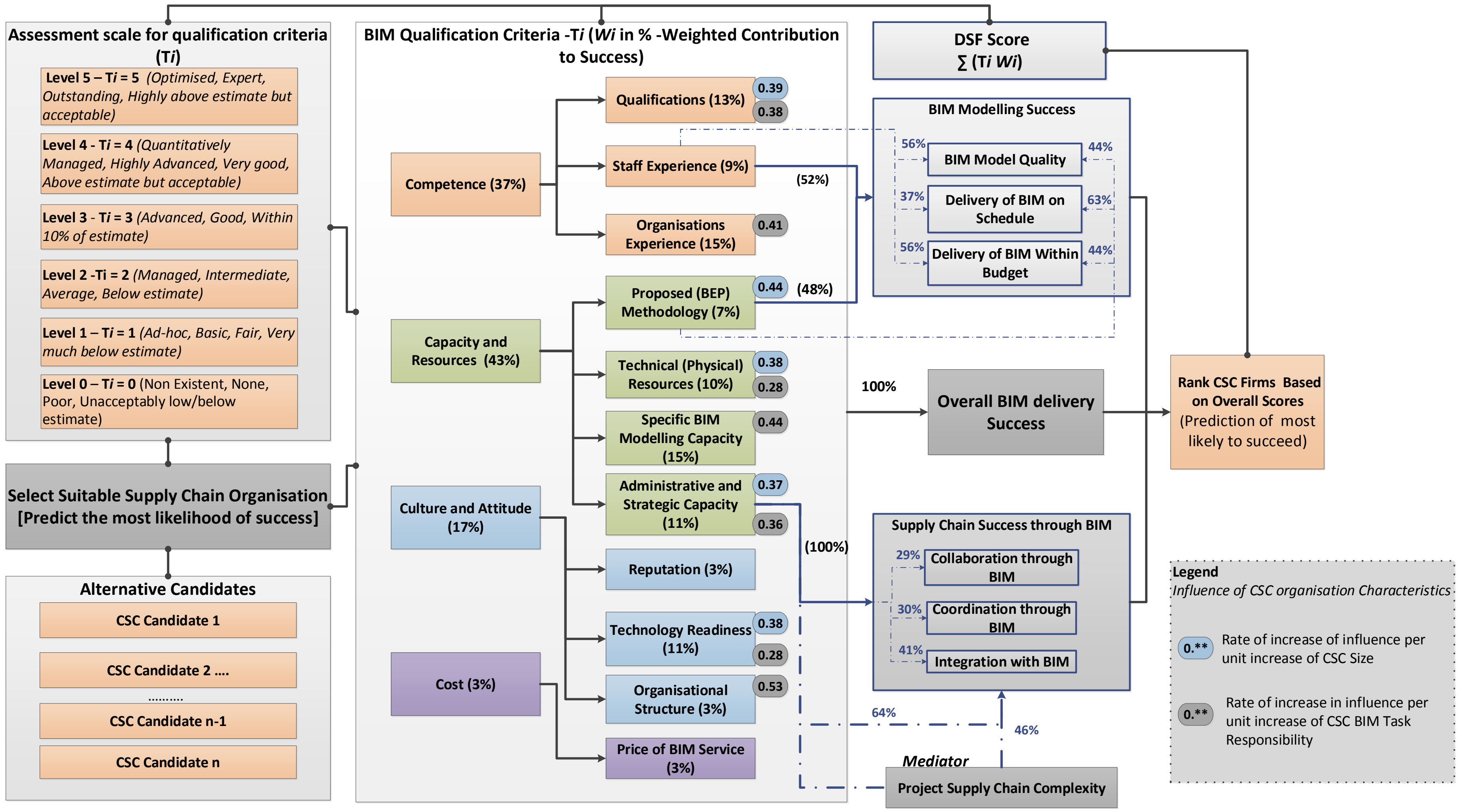


Figure 8.2: Decision Support Framework for Construction Supply Chain BIM Qualification

Following Succar *et al.* (2013), people and competence related criteria were allocated scales that can be rated between the '*lack of BIM skills, knowledge or experience'* to the possession of '*exceptional BIM skills and knowledge or extensive experience'*. Since process and technological related criteria are highly related to existing BIM capability frameworks, the generic descriptors of established process related capability maturity models was adapted (SEI, 2002; Succar, 2009; CIC, 2013b).

The scales adopted range from '*ad-hoc'* to '*optimised'* processes, with high level continuous improvement and predictable attainment of goals with reference to the specific qualification criteria under consideration. With regards to cultural and attitudinal criteria, a review of technology readiness, acceptance and diffusions models led to the adoption of scales ranging from '*technology scepticism'* to '*leadership and innovation'* in technology use (Rogers, 2003; Mahamadu *et al.,* 2014). Finally, guidance in PAS91 (2013) was followed to define scales for assessing cost or performance in situations, where CSC candidates are responding specifically to tender requirements (RFQ's and PQQs).

This includes assessment of the extent to which proposals meet project specifications (the EIRs). The scales for performance ranged from '*not meeting any of the requirements'* to '*exceeding specification'* with additional value added.

The norm for the evaluation of cost in construction studies is the closeness of proposed price to project estimates (Hatush and Skitmore, 1997). However, since this study looked at the impact of higher cost on delivery success the scale is adjusted accordingly. Thus, the lowest point on the scale for evaluating price represents '*low unacceptable prices'* for delivery of BIM, while the upper end of the scale represents the '*highest but acceptable price'*. The detailed description of the scales adopted for each category of assessment has been presented in Tables 8.4 to 8.7.

Table 8.4: Guidance for Competence Criteria Rating Scales for DSF

Maturity / Performance Level (T*i*)		Maturity / Performance Level Description	Key References
5	Optimised Expert Outstanding	• Extensive knowledge, refined level of skills and extensive experience in performing relevant BIM tasks. BIM training seamlessly integrated in organisations structure and culture. • Extensive practical application or experience in BIM processes and functions. • Extensive practical application or experience in BIM or collaborative project processes and functions.	(Discussions Section 8.2.3; CIC, 2013b; Succar *et al.,* 2013)
4	Quantitatively Managed Highly Advanced Very good	• Significant levels of knowledge, refined level of skills and practical experience in performing relevant BIM tasks consistently to high standards. High quality and relevant BIM academic or professional certifications. On-Demand BIM training. • Substantial practical application or experience in BIM processes and functions. • Substantial practical application or experience in BIM or collaborative project processes and functions.	
3	Defined Advanced Good	• There is a significant conceptual knowledge and practical experience in performing BIM tasks. There are relevant BIM academic or professional certifications. Regular BIM training for most personnel. • Adequate practical application or experience in BIM processes and functions. • Adequate practical application or experience in BIM or collaborative project processes and functions.	
2	Managed Intermediate Average	• There is evidence of solid conceptual understanding and some practical application of BIM tasks. Some relevant BIM academic or professional certifications. Training for some personnel. • Limited practical application or experience in BIM processes and functions. • Limited practical application or experience in BIM or collaborative project processes and functions.	
1	Ad-hoc Basic Fair	• There is only a fundamental understanding of BIM knowledge and skill areas. Inadequate academic or professional certifications. Ad-hoc BIM training. • There is virtually no practical application or experience of BIM tasks or functions. • There is virtually no practical application or experience of BIM or collaborative tasks or functions.	
0	Non-existent none Poor	• No acceptable level of knowledge, skills or evidence of practical application. No BIM academic or professional certifications. No training. • No evidence of practical application of BIM tasks or functions. • No evidence of practical application of BIM or Collaborative project tasks or functions.	

Table 8.5: Guidance for Capacity and Resources Criteria Rating Scales for DSF

Maturity or Performance Level (T*i*)		Maturity / Performance Level Description	Key References
5	Optimised Expert Outstanding	• BIM processes and functions are institutionalised and continuously improved. IT is the focus of organisations vision and mission. • Cutting edge equipment and technical infrastructure are available, standardised and key to organisational strategy. Specifications are the most up to date and of highest standards. • BIM processes and functions are institutionalised and continuously improved. BIM modelling processes are leading and can be described as best practices. • Satisfies the specified requirements or specifications. Exceptional understanding and evidence of ability to deliver to specification as well as additional value added through proposed innovative services.	(Discussions Section 8.2.4; SEI, 2002; Succar, 2009; CIC, 2013b; PAS91, 2013, PAS1192:2, 2013Kam et al., 2014; Review of 5 main contractor PQQ's U.K)
4	Quantitatively Managed Highly Advanced Very good	• BIM processes and functions are measured and controlled. Outputs are consistent and predictable. IT is key to organisations vision and mission. • Equipment and technical infrastructure are available, standardised and managed according to strategy. Specifications are recent and of high standard. • BIM processes and functions are measured and controlled. Outputs are consistent and predictable. BIM modelling processes are mainly based on best practice. • Satisfies the requirements or specifications. Above average demonstration of ability to deliver to specification with some additional benefits or value.	
3	Defined Advanced Good	• BIM processes and functions characterised for organisation and proactive. Outputs are consistent. IT is recognised as part of organisation vision and mission. • Equipment and technical infrastructure are widely available and standardised across organisation. Specifications are adequate. • BIM processes and functions characterised for organisation and proactive. Outputs are consistent. Industry standards are applied consistently to BIM modelling processes. • Satisfies the specified requirements and specification. There is a conceptual understanding and some evidence of an ability to deliver to requirements or specification. No additional value added services proposed.	
2	Managed Intermediate Average	• BIM processes and functions are mainly on project basis and often reactive. Outputs are inconsistent but traceable. IT recognised but not formally defined in organisational vision or mission. • Equipment and technical infrastructure are available but not standardised across organisation. Equipment specifications are not consistent. • BIM processes and functions are mainly on project basis and often reactive. Outputs are inconsistent but traceable. Industry standards are recognised with some applied to BIM processes. • Satisfies requirements and specification but a few reservations. There is a demonstration of an understanding of how to achieve requirements or specification but no evidence of this ability.	
1	Ad-hoc Basic Fair	• BIM processes and functions are poorly controlled and reactive. Outputs are inconsistent. IT is not well recognised in organisational vision or mission. • Equipment and technical infrastructure is generally inadequate or of low specification. • BIM processes and functions are poorly controlled and reactive. Outputs are inconsistent. Industry standards are recognised but inconsistently applied to BIM processes. • Satisfies some requirement and specifications with major reservations. There is minimal understanding or demonstration of ability to meet requirements or understanding.	
0	Non-existent None Poor	• No BIM processes and functions have been defined nor currently exist. No recognition of IT in organisational vision or mission. • No equipment or technical infrastructure to support tasks and functions • No BIM processes and functions have been defined nor currently exist. No recognition of industry standards. • Does not meet the requirements and specifications.	

Table 8.6: Guidance for Culture and Attitude Criteria Rating Scales for DSF

Maturity / Performance Level (T*i*)		Maturity / Performance Level Description	Key References
5	Optimised Expert Outstanding	• Exceptional performance and success on previous BIM projects. Previous stakeholders/clients extremely satisfied • Trail-blazer in digital technology use. Digital technology is highly diffused into organisations culture and way of work with degree of automation of task. • Exceptionally high levels of decentralisation and collaborative culture within organisation.	(Discussions Section 8.2.5; Cheung et al., 2002; CIC, 2013b) (Rogers, 2003; Succar, 2009O'Leary, 2009, Mahamadu *et al.,* 2014)
4	Quantitatively Managed Highly Advanced Very good	• Significant performance and success on previous BIM projects. Previous stakeholders/clients highly satisfied • Evidence of often early adoption of new technology and capable of supporting others to adopt. Digital technology is key to organisations processes. • High level decentralisation and collaborative culture within organisation.	
3	Defined Advanced Good	• Adequate performance and success on previous BIM projects. Previous stakeholders/clients satisfied • Digital technology is used but organisation cannot be considered leader in IT use. Digital technology is recognised as part of organisational processes. • Adequate decentralisation and collaborative culture within organisation.	
2	Managed Intermediate Average	• Limited performance and success on previous BIM projects • Digital technology cautiously used. Digital technology is recognised but not formally defined as part of organisational processes. • Limited level decentralisation and collaborative culture within organisation.	
1	Ad-hoc Basic Fair	• Minimum performance and success with previous BIM projects • Organisation is last to adopt digital technology. Digital technology is not well recognised as part of organisations processes. • Minimum level decentralisation and collaborative culture within organisation.	
0	Non-existent None Poor	• No success in previous BIM projects • There is evidence of prejudice, distrust or scepticism about digital technology and processes • No decentralisation and collaborative culture within organisation.	

Table 8.7: Guidance for Cost and Specified Performance Criteria Rating Scales

	Maturity / Performance Level (T*i*)		Maturity / Performance Level Description	Key References
Cost *	5	Highly above estimate but acceptable	• Price charged for BIM services is highly above initial preliminary estimate, but within client's budget, contingency or willingness to pay.	(Discussion Section 8.2.6 ; Review of PAS91, 2013)
	4	Above estimate but acceptable	• Price charged for BIM services is above initial project estimate but within client's budget, contingency or willingness to pay.	
	3	Within estimate	• Price charged for BIM services is within at least 10% of preliminary estimate.	
	2	Below estimate	• Price charged for BIM services is below (10%) preliminary estimates but acceptable.	
	1	Very much below estimate	• Price charged for BIM services is far below preliminary estimate with major concerns of ability to deliver BIM at that price.	
	0	Unacceptable	• Price charged for BIM services unacceptably low or beyond budget or client ability.	
Specified Performance / Direct Response to Tender Specifications	5	Outstanding	• Satisfies the specified requirements or specifications. Exceptional understanding and evidence of ability to deliver to specification as well as additional value added through proposed innovative services.	(Discussion Section 8.2.4; Review of; PAS91, 2013, PAS1192:2, 2013)
	4	Very good	• Satisfies the requirements or specifications. Above average demonstration of ability to deliver to specification with some additional benefits or value.	
	3	Good	• Satisfies the specified requirements and specification. There is a conceptual understanding and some evidence of an ability to deliver to requirements or specification. No additional value added services proposed.	
	2	Average	• Satisfies requirements and specification but a few reservations. There is a demonstration of an understanding of how to achieve requirements or specification but no evidence of this ability.	
	1	Fair	• Price charged for BIM services is far below preliminary estimate with major concerns of ability to deliver BIM at that price.	
	0	Poor	• Does not meet the requirement and specifications. Does not comply and/or insufficient information provided to demonstrate ability to deliver to requirements or specification.	

** NB: Scale for traditional selection, which is based economic advantage or closeness to project estimate/budget. However, for success prediction rely on the highest acceptable cost.*

Interviewees recommended neutrality in qualification metrics to aid adaptability to various CSC organisational scenarios. Generic scales were, therefore, adapted following the recommendations of Succar (2010) and Kam *et al.* (2013a) who also recommend the need for neutrality in BIM metrics in order to suit several contexts of application. The adapted scales were validated as appropriate for the DSF as discussed in next chapter (Chapter 9, *Section 9.2.2*). A six point scale is adopted with allocated points between zero ($Ti = 0$) to six ($Ti = 5$). The allocation of points follows BIM capability assessment recommendation as well as construction organisational selection framework recommendations in general.

8.5 CHAPTER SUMMARY

In this chapter the results from the data analysis have been discussed with a reflection on its relatedness and convergence with the literature. The discussions reveal areas of similarity as well as divergence from existing literature and knowledge. The use of the findings for the development of a DSF was also presented and discussed. The decision hierarchy consisting of critical BIM qualification criteria has been presented together with a computational framework for predicting CSC firms most likely to succeed in the delivery of BIM. In the next chapter the validation of the research findings is discussed.

CHAPTER 9: RESEARCH VALIDATION

9.1 INTRODUCTION

The main purpose of validation is to ascertain the credibility and generalisability of the results. This chapter discusses the validity of the findings based on the adoption of research validation processes proposed in previous construction management research. Validation aids the researcher to test the applicability of the findings in practice. According to Hair *et al.* (2010), where findings are derived from statistical models, validation provides an assurance that the models accurately measure the phenomenon they purport to measure. According to Fellows and Liu (2008), it further lends validity to the adopted research design. A number of approaches have been proposed for validation of the findings from research. The most widely cited methods of validation are categorised as either external or internal validation (Ahadzie, 2007; Al-Zahrani, 2013).

9.2 External Validation

External validation mainly relates to the establishment of how generalisable research findings are with cognisance of differences in the context within which the research is conducted (Fellows and Liu, 2008). The following are considered as the main categories of external validation:

- Replication;
- Boundary search; and
- Convergence analysis.

Research processes may be repeated to ascertain whether it results in the same outcomes (Rosenthal and Rosnow 1991). This process is referred to as replication. Despite being a robust approach for validating research, it is seldom used in social research particularly doctoral studies due to time, financial and logistical constraints (Brinberg and McGrath 1985; Ankrah 2007; Bashir, 2013). Thus, replication was not considered for validation of the research findings in this study. Similarly, the boundary search approach to validation is the process of identification of conditions under which findings do not hold (Brinberg and McGrath 1985). This method is most effective when a series of replication or convergence analysis are conducted over long periods of time. Boundary search was also not used for the same reasons cited for the non-use of replication (*ibid*).

Convergence analysis was, however, adopted as the main external validation approach for this study. Convergence analysis involves the use of different research methodologies to test for a level of agreement in findings (Denzin, 2009). The results from interviews went through some preliminary validation in the Delphi study. There was a general consensus from the Delphi findings that all the interview themes proposed as BIM qualification criteria are suitable for assessing CSC ability to deliver BIM during pre-qualification and selection. Furthermore, both qualitative and quantitative findings were collectively discussed to provide a holistic view of the research findings.

The use of research participants' opinion to validate findings is also regarded as an important approach to convergence analysis (Silverman, 2006; Creswell, 2009). This approach has been widely adopted for the conduct of construction management research (Ankrah, 2007; Anvuur, 2008; Manu, 2012; Bashir, 2013). In this study, a validation survey and expert respondent feedback was conducted. This involved a group of 12 experienced construction and BIM practitioners, seven of whom were engaged at previous phases of the data collection. The other five participants were recruited following the same procedure as the Delphi study (S*ection 7.3.1*). The validation panel consisted of experts with an average of 17.5 years of construction experience and 7 years in BIM or VDC technologies. The reliance on 12 experts is as a result of recommendations for use of few validation participants regarded as having expert knowledge on the subject (Anvuur, 2008). The background of respondents is detailed in Table 9.1.

9.2.1 The Validation Survey

The validation survey was conducted among six of the validation panel through a re-administration of questionnaires used in the main survey. The validation survey required participants to respond based on their general experience of BIM use rather than for a particular CSC firm or project, which was the case in the main survey. This was to allow for a comparison between generalised expert views and the main findings.

Table 9.1: Validation Respondent's Profile

ID	Role/Job Description	Experience (years)		Validation Survey	Respondent Feedback	Previous Research Involvement
		Construction	BIM/VDC			
V1	Building Design Manger	21	21		√	√
V2	BIM Manager	13	6	√		√
V3	Design Manager	15	5	√		√
V4	BIM Manager	20	5	√		√
V5	Managing Quantity Surveyor	17	10		√	
V6	Structural Engineer	6	3	√		√
V7	Design Technician	27	5	√		
V8	Architect	35	1		√	
V9	Architect	30	20		√	
V10	Lecturer/Researcher in BIM	15	4		√	
V11	BIM Manger	6	3		√	√
V12	Lecturer/Researcher in BIM	5	3	√		√
	Average/Total	17.5	7	6	6	7

Similar approaches have been adopted by Ankrah (2007) through a holdback sample and Al-Zahrani, (2013) through an expert validation survey. Agreement between the validation survey and the general survey was tested using Spearman's correlation coefficient following previous validation survey analysis in construction management research (Ling *et al.,* 2005; Wong and Li, 2010; Al-Zahrani, 2013). For this study, a test of agreement was performed between the mean responses of the general survey and the expert validation survey responses. The agreement test was performed on respondent's opinions about the influence of each of the 28 BIM qualification sub-criteria on overall delivery success. The main survey was in reference to a specific CSC firm, while validation participants answered based on their general expert opinion rather than for a specific CSC firm or project.

The test of agreement chosen is non-parametric, thus compared the rank order of variables in the main and validation surveys. The spearman's correlation coefficient (*rho*) resulted in a positive statistically significant value [rho = 0.771; $p < 0.05$; $n1$ = 64, $n2$ = 12]. This was indicative of acceptable level agreement between validation participants' opinion and the mean responses from the main survey. The results of the test of agreement are presented in Table 9.2.

Table 9.2: Test of Agreement for Validation of Findings

Qualification Criteria		**General Survey**			**Validation Survey**		
		N	Mean	Std. D	N	Mean	Std. D
Professional and Academic Qualifications	Key Technical Staff BIM Qualification	64	2.938	1.067	6	2.167	0.753
	BIM Staff Availability for Project	64	3.344	0.946	6	3.167	0.983
	Organisation's BIM Accreditations and Certifications	64	2.391	1.229	6	1.333	0.516
	Organisation's BIM Training	64	3.594	1.065	6	3.333	1.211
Staff Experience	Managerial Staff BIM Experience	64	3.563	1.125	6	3.833	1.169
	Key Technical Staff BIM Experience	64	4.203	0.858	6	3.833	1.169
Organisation Experience	BIM Software Experience	64	3.656	0.781	6	3.333	0.516
	Past BIM Project Experience	64	3.594	0.921	6	3.833	0.983
	BIM Experience on Similar Project	64	3.016	1.076	6	2.500	1.049
	Internal Use of Collaborative IT Systems	64	3.328	0.977	6	3.500	0.548
Administrative and Strategic Capacity	IT Vision and Mission	64	3.156	0.979	6	3.000	0.632
	Quality of BIM Implementation Strategy	64	3.594	0.849	6	3.667	0.817
	BIM Research and Development	64	3.250	1.084	6	3.667	1.211
Technical (Physical) Resources	Software Availability	64	3.500	0.960	6	3.167	0.753
	Data Storage (suitability and capacity)	64	2.828	0.901	6	3.000	0.894
	Network Infrastructure Availability	64	2.875	0.951	6	2.833	0.753
Specific BIM Modelling Capacity	BIM Standards	64	3.625	1.266	6	3.000	1.549
	Data Classification and Naming Practices	64	3.500	1.039	6	3.333	1.366
	Capability - Model Maturity	64	2.891	1.143	6	2.000	0.632
	Capability - LOD/LOI	64	3.688	1.125	6	2.833	1.329
Proposed Methodology	Suitability of Proposed BIM Execution Plans for Project	64	3.844	0.801	6	4.000	0.632
	BIM Vendor Involvement and Support	64	2.453	1.181	6	1.833	0.753
Reputation	Reputation of Organisation	64	2.453	1.181	6	2.000	1.095
Technology Readiness	Attitude and Willingness	64	3.359	1.060	6	3.167	1.472
	Awareness of BIM Benefits (in project context)	64	3.734	0.802	6	3.333	0.817
	Extent of IT Support to Core Business and Processes within Firm	64	2.969	1.098	6	3.000	1.265
Organisational Structure	Organisational Structure - level of decentralisation	64	2.781	1.105	6	2.500	1.225
Cost	Cost/Price of BIM Service	64	3.188	0.906	6	3.000	0.632
Test of Agreement Between Surveys Spearman's rho [rho=0.771; $p < 0.05$]							

9.2.2 Respondent Feedback on Research Findings

Six members of the validation panel participated in the respondent feedback survey. This involved presentation of the research findings for participant perusal after which they provided their opinions about validity based on their professional experience. The feedback sheet included nine Likert-scale and some open ended questions. Discussions were also held with participants to help understand their responses. The Likert-scale questions required participants to rate their agreement with research findings, as well as usefulness of proposed DSF in practice. The results are presented in Table 9.3. This approach is considered one of the best approaches for validating research particularly where statistical analyses have been applied (Brinberg and McGrath 1985; Anvuur, 2008; Bashir, 2013).

Table 9.3: Results of Respondent Feedback for Validation of Findings

Validation Feedback	**Response (%)** *(n = 6)*					
	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree	Total
Validity of Key Research Findings						
The criteria identified are relevant to BIM qualification of the CSC.	16.7	66.7	16.7	0.0	0.0	100.0
The criteria identified are adequate for BIM qualification of the CSC.	16.7	66.7	16.7	0.0	0.0	100.0
The criteria weightings (in %) depicting the relative contribution of BIM qualification criteria to overall delivery success is realistic.	0.0	66.7	16.7	16.7	0.0	100.0
To what extent do you agree with the findings about the most significant contributors to BIM Modelling success (i.e. model quality, delivery of models on schedule and within budget)?	16.7	83.3	0.0	0.0	0.0	100.0
To what extent do you agree with the findings about the most significant contributors to CSC through BIM (i.e. collaboration, coordination and integration)?	0.0	50.0	16.7	16.7	16.7	100.0
BIM modelling success (i.e. quality, delivery of BIM on schedule and within cost) is not dependent of project complexity.	0.0	50.0	33.3	16.7	0.0	100.0
CSC success through BIM (i.e. collaboration, coordination and integration) is more likely on projects with complex supply chains.	0.0	66.7	16.7	16.7	0.0	100.0
Relevance and Usefulness of DSF						
DSF is useful and relevant to pre-qualification and selection of CSC on BIM projects.	33.3	50.0	16.7	0.0	0.0	100.0
Description of criteria attached rating scales are very relevant to CSC pre-qualification and selection.	0.0	66.7	33.3	0.0	0.0	100.0

Similar approaches were followed in studies that applied multivariate statistical techniques for data analysis (Ankrah, 2007; Al-Zahrani, 2013). The results of the respondent feedback survey were based on simple percentages of the Likert-scale responses. From the respondent feedback analysis, there was a high level of agreement with the overall research findings as well as the relevance of the DSF. This is discussed below together with comments from the participants.

9.2.2.1 Relevance and Adequacy of BIM Qualification Criteria

Majority of the respondents were of the opinion that BIM qualification criteria were both relevant and adequate for assessing CSC organisations suitability during pre-qualification or selection. Most of the respondents (66.7% agree and 16.7% strongly agree) agreed that qualification criteria proposed from the study was adequate as well as relevant. From the open ended questions a few observations were made about the structure of criteria hierarchy.

One of the respondents opined that staff and organisational experience should be grouped under the same category. "*I suggest that experience should be in one category…I think the staff and organisation's experience are very similar"* [V 11]. Most of the comments showed significant agreement with the relevance of the qualification criteria proposed in the study in general: *"I strongly agree with these criteria…..I think they are the type of questions I have seen in most BIM PQQ's that I have come across* " [V 5].

9.2.2.2 BIM Qualification Criteria Contribution to Delivery Success

The majority of respondents agreed that the BIM qualification criteria's relative contribution to delivery success was realistic. Most (66.7%) of the respondents agreed with the research findings with respect to the weighted contribution to delivery success. Respondents were, however, of the opinion that there were other factors that may also affect delivery success. This is exemplified in the following quote: "*I strongly agree they look realistic from my experience…. success is also influenced by many* *other things… so selecting consultants or subcontractors should not be solely based on the framework"* [V 5].

With regards to the predictors of BIM modelling success, all respondents (100%) agreed that staff experience and proposed methodology are the most important criteria. This is evident in the following quotes: "*so far as I am concerned, experience is the most important criteria for assessing BIM capability…so I agree 100% with this research*" [V 7]. *"I have always said that the BIM execution plan is the most important document for a BIM project"* [V 5]. "*For any of the supply chain to be on a project, it is good to know their plan or some sort of strategy they plan to use….we ask for method statements in tender, this has to now include BIM plans of work, because without this, to be honest I don't see how you can monitor or control the project"* [V6].

More respondents (50%) agree (against 33% disagreement) that administrative and strategic capacity is most influential on CSC success through BIM. Similarly, half of respondents (50%) agreed that project complexity did not necessarily affect the attainment of BIM modelling success (against 33% disagreement). Finally, the majority of the validation experts agreed (67.7%) that the attainment of collaboration, coordination, and integration through BIM mostly occurs on projects with complex supply chains. One respondent, however, noted that: *"yes BIM is good for complex projects but it must also be noted that failure can also be catastrophic…. when things go wrong and the supply chain is complex*" [V 9].

9.2.2.3 Relevance of Decision Support Framework

Finally, the majority of the respondents (*strongly agree* - 33.33% and *agree* - 50.00%) were of the opinion that the DSF is relevant to CSC pre-qualification and selection. The proposed description of criteria and scales was regarded as adequate according to the majority of the respondents (67.67%). The major observation made by respondents was the fact that mathematically based frameworks should not be the sole methodology for selecting the CSC. According to respondents, the experience of evaluators should be relied on in addition to DSF's recommendation which is based on mathematical scoring or allocation of points. One respondent noted that: "*selection systems must not exclude innovation by approving people who know how to answer questions (for example PQQ questions) well*" [V 8].

The following were also recommended to make the DSF more relevant in practice.

- Each of the 28 critical BIM qualification sub-criteria should be broken down into questions that can be drafted into a qualification forms or questionnaires (PQQ's). In relation to this recommendation the validation experts believed the PAS1192 (2013) recommend supply chain capability summary (SCCS) and CPIx forms were limited in their coverage of some of the BIM qualification criteria proposed.
- The DSF diagram will be easily understood by academics more than practitioners. Industry implementation of DSF should be based on forms and questionnaires.

9.2.3 Internal Validation

Internal validation is used to describe the process for the determination of the extent of bias in research. Good research design is regarded as the primary determinant of internal validity (Fellows and Liu, 2008). The approaches for assessing internal validity in construction management related studies include comparison of findings with published studies or literature (Proverbs, 1998; Xiao, 2002; Ankrah, 2007; Manu, 2012). In this study, the convergence between the findings and many other studies is demonstrated in *Sections 8.2 to 8.4*, where empirical research with similar findings have been cited or cross referenced. A discussion that draws insights from previously published work is also described as an important approach in demonstrating internal validity (De Vaus, 2002). Furthermore, the discussions highlighted high level of convergence with existing knowledge on BIM capability assessment, SCM, as well as CSFs in BIM implementation. The proposed DSF relies on findings from all phases of the research, as well as existing literature. While the coefficients and computational frameworks are mainly from the quantitative phases, the description of criteria and rating guidance was largely based on qualitative data and literature (S*ection 8.4*).

Publication of work: Publication of research ideas and outputs in doctoral studies are regarded as important contributors to internal validity. The development of the research as well as the refinement of the objectives benefited from the peer review process for academic conferences and journal publication. A detailed list of author's publications is presented in Appendix G. This includes publications that aided the identification of the research problem, as well as other publications that have been cited as part of the literature review and discussions in the thesis report. The critical BIM qualification criteria identified from the three phases of data collection has been published in peer reviewed journal. The peer review process for publication presents an opportunity for the refining research ideas methodologies, meanings (Proverbs 1998; Ankrah, 2007).

Some other publications, which are not directly related or cited in this thesis, but were as a result of the overall research training during the research period, have also been provided in Appendix G.

9.3 CHAPTER SUMMARY

Various tests of validity have been used to support the generalisability of the findings from this study. The main purpose of validation is to ascertain how valid the results are, as well as their relevance in practice. In this chapter the validity of the findings has been presented and discussed. This included external and internal validation procedures adopted. The next chapter presents the conclusion drawn from the research findings.

CHAPTER 10: CONCLUSION AND RECOMMENDATIONS

10.1 INTRODUCTION

This chapter presents the conclusions drawn from the entire research. The conclusions are discussed in relation to each of the research objectives. The contribution of the research findings to knowledge, as well as implications for practice, is also discussed. The chapter is concluded with an outline of the implications for future research, together with an acknowledgement of the limitations of the present study.

10.2 REVIEW OF RESEARCH OBJECTIVES

With the emergence of BIM, a critical criterion for selecting the Construction Supply Chain (CSC) for projects is the ability to deliver through BIM. However, a review of the extant literature revealed a lack of frameworks and toolsets specifically developed to aid qualification of the CSC to be part of BIM-enabled projects. There is lack of clarity on the BIM capability attributes relevant to the pre-qualification and selection process, thus, suitable for use as qualification criteria. Furthermore, there is a need for an understanding of the relationship between often pre-emptive qualification criteria and a CSC organisation's propensity to successfully deliver through BIM.

The aim of the research was, therefore, to examine the influence of BIM qualification criteria on the successful delivery of BIM on projects in the CSC context. This was to aid the development of a novel approach in order to assess a CSC firm's likelihood of succeeding in the relevant areas on a BIM-enabled project through the pre-qualification or selection process. The research further aimed to develop a Decision Support Framework (DSF) capable of prioritising CSC firms based on their propensity towards BIM delivery success.

Five research objectives were proposed to achieve the aims of this study. A sequential exploratory mixed method design was subsequently engaged for the empirical investigation (Chapter 5). The attainment of these objectives is reviewed in this section.

Objective 1: '*To review literature in order to develop an understanding of BIM qualification criteria for the CSC as well as their role in successful delivery of BIM in the supply chain context'.*

This objective was addressed in Chapters 2 to 4. Following an extensive review of the literature, it was revealed that there is a proliferation of BIM capability assessment frameworks and toolsets, as well as theoretical propositions on BIM capability evaluation. Despite the emergence of research on BIM capability, there are very few studies specifically looking at BIM qualification (pre-qualification and selection) of CSC firms for projects. Furthermore, there are no studies that empirically quantify the influence of BIM qualification attributes on the attainment of BIM delivery success. The review concluded that several limitations exist in relation to the applicability of existing capability frameworks for the BIM qualification process relevant to the CSC (specifically for pre-qualification and selection). Despite the existence of several propositions on quantifying the ability to deliver BIM, there remains a lack of empirical evidence. Thus, the reliability and validity of most BIM capability frameworks remains questionable. More significantly, there is a lack of a comprehensive and empirically tested framework to aid BIM qualification of the CSC. Most importantly, there is a dearth in knowledge about the relationship between often pre-emptive qualification criteria and the influence of the attributes measured pertinent to delivery success.

Another finding at this stage was the proliferation of guidance and standards documents, which require UK CSC to demonstrate their ability to deliver through BIM (including CIC, 2013a; PAS1192:2 2013; PAS91, 2013). However, since these are mainly guidance documents, they do not prescribe specific BIM qualification criteria nor provide a holistic decision framework with clear delineation of the criteria's relative importance, or priority weightings. Based on the identification of themes regarding BIM capability in general, a preliminary research instrument was developed to solicit BIM expert views on which BIM capability attributes are relevant and appropriate as qualification criteria, towards the selection of CSC firms in order to deliver through BIM in projects.

Objective 2: '*Identify and categorise BIM qualification criteria in order to develop a hierarchy of assessment criteria for CSC pre-qualification or selection purposes'.*

Based on interviews with eight (*n* = 8) BIM experts with CSC procurement experience within the UK, eleven BIM qualification criteria were identified consisting of 45 sub-criteria. These were categorised under four main assessment areas:

- The first category was *Competence* criteria, which included attributes related to BIM knowledge and skills demonstrated by experience or academic and professional certification;
- The second category was *Capacity and Resources,* which included criteria related to process and technological maturity and physical resources for BIM implementation and delivery;
- The third category was *Culture and Attitude* representing soft situational enablers relating to attitudes towards BIM and culture. This consisted of soft behavioural predispositions towards BIM such as their willingness and technology readiness; and
- Finally, *Cost* was identified as a primary BIM qualification criterion similar to the wider reliance on price in construction pre-qualification and selection activities.

These four categories of criteria formed the first level of a hierarchy of BIM qualification criteria. The four categories of qualification criteria were used as a structure for further identification, eleven themes from the interviews subsequently represented the main BIM qualification criteria in the second level of the criteria hierarchy. The qualification criteria identified for this level were: *Professional and Academic Qualifications, Staff Experience, Organisations Experience, Administrative and Strategic Capacity, Technical (Physical) Resources, Specific BIM Modelling Capacity, Proposed Methodology, Reputation, Technology Readiness, Organisational Structure* and *Cost* of BIM service. Interviewees further proposed sub-criteria, which were categorised under each of the BIM qualification criteria. This formed the final level of the hierarchy consisting of 45 sub-criteria in total. The analysis that resulted in the proposed BIM qualification criteria hierarchy was presented in Chapter 6 and discussed in Chapter 8, *Section 8.2.2*.

BIM qualification criteria definitions and classifications generally align with BIM capability criteria previously proposed by many studies. A significant degree of uniqueness is, however, identified with the inclusion criteria that examine contextual abilities that are specific to the context of evaluation (specific project or client requirements). Since most existing frameworks pertain to BIM implementation, they tend to focus generic indicators of internal BIM process maturity or capacity. The 45 criteria proposed in this study, however, included several project or scenario-specific criteria including, cost, and proposed BEP suitability for EIR's, experience on similar projects and staff availability for projects.

Objective 3: '*Identify the most critical criteria and prioritise them based on their relative contribution to the successful delivery of BIM'.*

The third objective was to identify the most critical criteria in order to reduce the 45 proposed sub-criteria to a more parsimonious set of BIM qualification criteria. A two-round Delphi study was conducted to allow experienced construction practitioners in BIM to re-evaluate proposed BIM qualification criteria. The Delphi study involved 30 participants in the first round and 25 in the second round of iterative administration of surveys. Consensus was reached on a set of 28 sub-criteria as the most critical across the eleven proposed BIM qualification criteria areas. Consensus was based on a computation of inter-rater agreement (r_{wg}) with the aid of R software. The criteria retained as the most critical in the qualification of CSC organisations for BIM-enabled projects in presented Table 10.1.

Table 10.1: Summary of Most Critical BIM Qualification Criteria

Qualification Criteria		Description/Sub-Criteria
Competence	Professional and Academic Qualifications	Key technical staff BIM qualification; BIM staff availability for project ; Organisation's BIM accreditations and certifications; and Organisation's BIM training arrangements
	Staff Experience	Managerial staff BIM experience; and Key technical staff experience
	Organisation's Experience	BIM software experience; Past BIM project experience; BIM experience on similar project; and Internal use collaborative IT systems
Capacity and Resources	Administrative and Strategic Capacity	IT vision and mission; Quality of BIM implementation Strategy/Plans; and BIM research and development
	Technical (Physical) Resources	Software available to firm; Data storage (arrangements/capacity) within firm; and Firms' network infrastructure
	Specific BIM Modelling Capacity	BIM Standards (compliance with best practice); Data classification/naming practices; Model maturity expertise; and Model LOD/LOI expertise
	Proposed Method of BIM Delivery	Suitability of proposed BEP in meeting project EIR; and BIM software vendor involvement and support for project
Culture and Attitude	Reputation	Reputation of firm in BIM - Past Performance
	Technology Readiness	Technology Readiness (attitudes towards new technology); Awareness of BIM benefits (in project context); and Extent of IT support to core business or processes within firm
	Organisational Structure	Organisational structure - levels of decentralisation
Cost		Prices charged for BIM services

The relative importance of these capability attributes, their use as BIM qualification criteria, as well as their influence on BIM delivery success, were subsequently determined based on a structured questionnaire survey of practitioners on BIM-enabled projects (n = 64) in the UK. The assessment was based on individual project participant's perceptions about the performance of project CSC participant's on current or recently completed projects in relation to six key BIM success areas: quality of BIM; delivery of BIM on schedule; delivery of BIM within budget; collaboration; coordination; and integration of the CSC through BIM; as well as overall BIM delivery success.

Based on an analysis of the variables' mean weighted contributions, *Capacity and Resources* related criteria were found as most likely to influence overall delivery success. This was followed closely by *Competence* related criteria. This finding generally aligned with existing knowledge about the importance of process, technology and information management attributes as the primary indicators of capability. It was also revealed that (as expected), there is a high degree of connectedness between the possession of a BIM capability and the likelihood of delivery success in general. However, a more detailed analysis of criteria revealed varying levels of importance in relation to each individual criterion's importance as a capability metric and, on the other hand, its contribution to various dimensions of BIM delivery success, respectively. For instance, technological and infrastructure requirements are perceived as important qualification criteria, yet, they were found to contribute less to delivery success in comparison to criteria, such as experience and specific BIM modelling process maturity and expertise. Thus, the findings support a notion that when the CSC is being qualified or selected for a project, infrastructure capacities only represent a basic representation of their suitability rather than a clear indication of likelihood of success. However, in conjunction with leveraging more of the tangible and intangible benefits of BIM, information related process maturity, availability of experience as well as individual competence is paramount.

Objective 4: *'Ascertain the impact of qualification criteria on specific BIM delivery success areas in the Supply Chain Context of BIM use'.*

It has been advocated that to mitigate the risk of failure, there is a need for an understanding of the relationship between attributes used in BIM qualification criteria and their influence on desirable BIM deployment objectives. One of the critical objectives of this study was, therefore, to identify the relationship between critical BIM qualification criteria and key BIM delivery success indicators in the CSC context. Two dimensions of success indicators were drawn from the literature and subsequently investigated (S*ections 4.3.3* and *4.3.5*). The first dimension was '*BIM modelling success'* representing the traditional *iron triangle* view of success. This 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. The objectives assessed were collaboration, coordination and integration of CSC through BIM.

Based on the survey data, multiple linear regression models were developed using SPSS v19 statistical analysis software. The associated regression equation coefficients revealed that *Staff Experience* and *Proposed Methodology* were the most critical predictors of BIM modelling success. *Staff Experience* (mainly in key technical staff) was most associated with the delivery of quality BIM models and delivery of BIM within budget, while suitability of *Proposed Methodology* for BIM execution was mostly associated with attainment of BIM deliverables on schedule. While there is lack of theoretical insights on the factors that contribute to quality of BIM modelling, as well as the delivery of BIM within budget, this study highlights the importance of individual staff BIM competencies, especially, the accumulation of knowledge and skills as a result of previous or prolonged BIM usage (experience). Thus, it shows that despite the process-laden nature of BIM development, organisational process maturity contributes less to BIM modelling success (quality, schedule and budget) as compared to individual competencies, particularly, BIM experience of personnel. With respect to delivery of BIM models on schedule, the findings highlight the importance of effective planning with the identification of *Proposed Methodology (Execution Plan)* as the most critical criterion. BIM execution planning is a relatively novel concept, which is still under development and review. However, this study makes a case for the need for an emphasis on development of tailored BEPs that respond to project requirements and specifications. From the findings the suitability of BEP's for projects is one of the most critical determinants of BIM modelling success. The study, therefore, highlights the importance of recommended documents (per the current standards for BEP content (PAS 1192:2, 2013)), such as the Master Information Delivery Plan (MIDP), the Project Implementation Plan (PIP) and the Task Information Delivery Plan (TIDP) based on empirical analysis of CSC delivery performance on UK projects. The finding further highlights the need for a focus on individual personnel experience in the review of responsibility matrices as part of tender returns or BEPs so as to achieve quality BIM deliverables within budget.

In relation to CSC success through BIM (collaboration, coordination and integration), there was generally lower likelihood of their attainment on projects as compared to BIM modelling success overall. However, in cases where they were attained, it was found to have been influenced mostly by *Administrative and Strategic Capacity* of the CSC organisation. These relate to more indirect performance expectations of BIM, since issues such as collaboration, coordination and integration are influenced by other structural and commercial imperatives in the CSC relations. The study, however, highlights the need for strategy and administrative related capacities in order for BIM to leverage key SCM performance expectations. Administrative and strategic capacity, as investigated in the study include *IT Vision and Mission, Quality BIM Implementation Strategy* and *R&D*. Findings, thus, suggest that CSC and SCM must be synergised with the broader strategies of IT implementation vision as well as innovation in the application of BIM within a CSC organisation in order to attain related success. Another interrelated finding was that CSC success through BIM was mediated by the level of supply chain complexity. This also indicates that there is more value in leveraging CSC objectives through BIM on projects with relatively complex supply chains.

Pearson's (Product-moment) coefficients (*r*), together with an analysis of variance (ANOVA) within the survey data set was further used to delineate influence of project and CSC characteristics on the levels of influence of qualification criteria, on success. The related findings showed that *Material and Product Suppliers* and *Architectural Design Consultants* were found as the most likely to achieve desirable levels of success in BIM modelling. *Proposed Methodology* was found to influence delivery success to a higher extent within larger CSC organisations, supporting a notion that BIM execution planning is more important to larger organisation's operations than smaller organisations. It was also found that as BIM task responsibility increases the levels of decentralisation in organisational structures became slightly more relevant to delivery success. The extent of influence of these project complexity and CSC characteristics was, however, generally low and in some cases marginal. The findings related to *Objective 4* were presented in Chapter 7 and discussed in Chapter 8, *Section 8.3*.

Objective 5: '*Develop and validate a Decision Support Framework (DSF) to aid the pre-qualification or selection of CSC for BIM-enabled projects'.*

Qualifying the CSC for BIM-enabled projects is a multi-criteria decision process and requires a structured approach to decision making. This helps evaluators to avoid over reliance on subjective judgement. In order to enhance the information available to decision makers, a BIM qualification DSF was proposed to provide an overall coherent and evidence based guide for pre-qualification or selection of CSC on BIM-enabled projects. The DSF relies on the critical qualification criteria derived from this study, as well as coefficients and weights derived from the inferential statistical analysis in relation to the contribution of criteria to delivery success. The main architecture of the framework was based on a computational approach that applies relevant criteria in relation to their weighted contribution to various delivery success indicators. The summation of overall scores was then used as basis to rank CSC candidates based on most likely to succeed in three areas, overall success, BIM modelling success and CSC success through BIM. Advisory notes pertaining to the descriptions of criteria and influence of CSC and project characteristics have also been provided. CSC organisation's performance in relation to each criterion is based on an adaptation of performance assessment scales traditionally used in pre-qualification and selection, as well as maturity levels used in BIM capability maturity and readiness modelling. The framework has been outlined in *Section 8.4*.

Validation of the research findings and DSF was achieved through external and internal sources. The external validation included a respondent validation through convergence analysis. Twelve (12) industry experts with extensive CSC procurement or BIM experience were surveyed to ascertain their agreement with the key research findings. There was overall agreement on the validity of the findings, as well as the usefulness for the DSF in practice. Recommendations for improvement were also suggested. The internal validation primarily consisted of an analysis of the convergence between research findings and published research. This also highlighted significant areas of concurrence as well as divergence. The validation process for the findings and the DSF was detailed in Chapter 9.

10.3 RESEARCH LIMITATIONS

Despite the relevance of findings of the research, there are a few limitations worth acknowledging.

- A review of the survey respondent's backgrounds revealed many of the CSC organisations assessed were design consultants (architects and engineers) with a few main and sub-contractor organisations. Most of them have a high level design responsibility and work between the middle to the top tier of the CSC. Hence, the results do not fully reflect lower tiers of the CSC and other segments of the CSC. This is, however, largely due to reported lack of usage of BIM by lower tier CSC organisations that often have less design responsibility and digital technology know-how.

- The research was cross-sectional in nature, thus, it provides a snapshot view at a particular point in time. It can be argued that findings do not reflect likely changes in the relationships between qualification criteria and success as BIM implementations as the concept of BIM keeps evolving.
- The study was based on expert and professional views of individuals within UK organisations and BIM projects, therefore findings may be peculiar to the UK context of BIM use.
- Despite the mixed methodological strategy adopted, there was an extensive reliance on quantitative techniques in the analysis of data. It is, however, accepted that, where mixed methods are engaged, one particular research method often dominates the design (Creswell, 2009). While the quantitative strategies provide a high degree of assurance of validity and reliability, they tend to answer the questions related to "what" at the expense of "why".

In order to increase reliability generally, research relied on senior and experienced practitioners who have the know-how and strategic awareness in order to minimise any potential misjudgements. Convergence between various aspects of the findings and literature further demonstrate the reliability of expert and professional views in the investigation of the phenomenon.

10.4 REVIEW OF RESEARCH FINDINGS

From the findings, the need for knowledge about the influence of qualification criteria on BIM delivery success is reinforced as a means of enhancing the CSC pre-qualification or selection process. While acknowledging the most critical BIM qualification criteria for the CSC, the research goes further to explain the mechanism by which BIM qualification attributes influence delivery success.

- The study highlights the multi-dimensional nature of the relationship between the possession of an ability to deliver BIM and the actual delivery of intended benefits or objectives. It is concluded that individual BIM capability attributes influence various aspects of BIM delivery success to different extents and this must be taken into consideration when selecting CSC candidates based on BIM qualification.
- The study also highlights the importance of capacity and resources related criteria to the BIM qualification process, as well as the attainment of BIM delivery success. Specifically, technological process maturity within a CSC organisation, which enables the production of and seamless sharing of BIM deliverables, such as models and other data. This includes the availability *BIM Standards*, *Data Classification and Naming Practices, Model Maturity Capacity* and *LOD/LOI Capacity*. In addition to these, collective knowledge and skills acquired from previous experience of BIM use is identified as the single most influential criteria on BIM delivery success in general.
- The findings reveal that despite the process laden nature of BIM development, organisational process maturity contributes less to BIM modelling success (quality, schedule and budget) as compared to individual competencies, particularly the level of staff BIM experience. Furthermore, BEP suitability is most influential to BIM modelling success in relation to delivery of outputs on schedule.
- From the research findings CSC and SCM must be synergised within the broader strategic management of IT implementation and administration in order to attain objectives such as collaboration, coordination and integration of the CSC through BIM. According to the research findings, technical capacities and process maturity play less significant role in the attainment of objectives related collaboration, coordination and integration of the CSC through BIM.

10.5 CONTRIBUTION TO KNOWLEDGE

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. Prior to this study, there was limited quantitative evidence on the relative significance of the BIM capability attributes and their use as criteria for the qualification of organisations for BIM-enabled projects. Furthermore, there is a dearth in knowledge regarding the causal influence of such criteria and delivery success especially in the CSC context of BIM use. The main theoretical contributions of this study are summarised below:

- The findings provide empirical evidence on the need for the prioritisation of BIM qualification criteria based on criteria relative influence on desirable success indicators rather than the basic determination of their possession of an ability to use BIM as widely proposed in existing frameworks. This stems from the fact that the relationship between BIM capability and delivery success is multi-dimensional rather than unilateral, as theorised in many existing BIM capability assessment frameworks and studies. Various capability attributes relied on as BIM qualification influence the various BIM delivery objectives to different extents. Thus, the prioritisation of criteria during an assessment must be based on their relative contribution to all relevant areas of success in order to provide a holistic view. Prioritisation of criteria in existing frameworks is, 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. Thus, this study provides 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 BIM within budget; collaboration, coordination and the integration of CSC through BIM.

- 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. Thus, the study lends credence to the importance of a softer technology deterministic view of BIM, where the technological artefacts must be viewed in relation to their interactions within the people and socio-political structures of construction organisations.
- The uniqueness of the BIM qualification process from other capability assessments is highlighted in this study. The findings reinforce the need for the consideration of generic capabilities as well as an ability to demonstrate how inherent capabilities can be applied to specific project contexts. Hitherto, no capability assessment toolsets have considered both categories in a single framework. The findings therefore provide insight about the relative importance of criteria across these two categories. For instance, the study has empirically established a significant relationship between generic competencies related to staff experience and BIM modelling quality as well as delivery within budget. On the other hand project specific BIM execution planning capabilities are more influential on the delivery of BIM deliverables on time.
- Despite calls for a soft approach to BIM readiness assessment, the findings show that such assessments may be more challenging in practice as a result of the often psychometric measures required. Thus, there are generally less numbers of proposed qualification criteria in the culture and attitudinal readiness category. While some existing studies have prioritised soft measures as most important, this study found related measures (culture and attitude) as

less important in comparison to knowledge, skills, process and infrastructure capabilities during prequalification or selection of CSC.

- Additionally, the applicability of the multiple linear regression technique in predicting successful delivery of BIM based on qualification criteria influence has been demonstrated. The use of multiple regression coefficients for prioritising qualification criteria has been previously proposed for construction pre-qualification and selection problems. This study, therefore, provides some practical steps towards its adoption in the BIM context through development and validation of a DSF with key inputs from multiple linear regression model coefficients, together with other multi-variant statistical analysis. The novel multiple regression models depicting a mathematical relationship between key qualification criteria and their implications on other relevant BIM delivery success are presented in Equation 10.1 and 10.2.

Equation 10.1: Regression Equation for Predicting BIM Modelling Success

BIM MODELLING SUCCESS [Quality – Schedule - Budget] = 0.857 + 0.483 (Staff Experience) + 0.447 (Proposed Methodology)

Equation 10.2: Regression Equation for Predicting CSC Success through BIM

OVERALL SUPPLY CHAIN SUCCESS THROUGH BIM [Collaboration – Coordination - Integration] = 1.483 + 0.595 (Administrative and Strategic Capacity)

10.5.1 Practical Contribution

A practical DSF has been proposed to aid decision making in CSC selection for BIM-enabled projects. The DSF proposes the use of empirical validated data on the criteria priority weights that depict the likelihood of delivery success in multiple areas. Based on feedback from respondent validation, this approach has relevance to the pre-qualification and selection process.

A clear picture about the critical BIM qualification criteria required for pre-qualification and selection of CSC for BIM-enabled projects has been provided based on empirical evidence and perspectives of practitioners on BIM-enabled projects in UK. The study has also contributed to the knowledge on the use of multi-variant statistical (Multiple linear regression) techniques to predict CSC candidate BIM delivery success in practice. This provides pathways for relying post-project BIM performance evaluations to enhance the pre-qualification and selection practices for BIM-enabled projects.

10.6 CONCLUSIONS

Some theoretical justifications have been provided in relation to BIM capability and approaches to assessment. However, there is still a dearth in knowledge about the nature of relationship between BIM capability and the delivery of specific BIM objectives, particularly in the CSC context. This study therefore, provides new insight into BIM capability in a context hitherto, not adequately explored. The novelty of this study lies in the development and validation of a framework that can assist in the pre-qualification or selection of CSC organisations through predicting their propensity towards success in different key success areas. In so doing, the gaps in the extant literature regarding specifically tailored frameworks for pre-qualification and selection process for the CSC on BIM-enabled projects has been addressed by this study.

10.7 RECOMMENDATIONS

Based on the findings and conclusions the following recommendations have been put forward.

10.7.1 Recommendations for Industry

The implications of the research findings and on the practices within industry is summarised as follows:

- Pre-qualification and selection must not be based on an assessment of the ability to deliver BIM but also an estimation of likelihood of success in relation to key delivery objectives.
- There is a need for close attention to be paid to BIM execution planning in order to improve delivery success rates per project especially in relation to the efficiency of BIM delivery.

- CSC organisations must place emphasis on developing BIM process maturity in addition to acquisition of 'hard' physical resource capacity building.
- There should be concerted efforts towards the strategic and administrative level capabilities in order to effectively integrate BIM into the wider SCM agenda. This mainly relates to vision, implementation planning and allocation of resources for BIM delivery.
- BIM experience within organisations, as well as among staff, is critical to BIM delivery success. Therefore, while the CSC builds their portfolio of BIM projects, efforts must also be made to engage personnel who already have requisite BIM delivery experience. This will also give opportunity to inexperienced personal to learn from more experienced ones.
- Lastly, the importance of certification of BIM capability and competence of the CSC by third party accreditors or institutions is highlighted. It has been empirically established that CSC organisations that have been externally certified for BIM capability or with employees with professional as well as academic BIM qualifications have higher likelihood of BIM delivery success. Secondly, the certificates and degrees provide the most valuable evidence of BIM capability and maturity during the pre-qualification and selection process which are often undertaken in conditions that prevent extensive evaluations.
- Principal suppliers must adopt BIM qualification as part of strategic CSC management, as well as performance management, given the rising demand for fully integrated BIM projects.

10.7.2 Recommendations for Policy Makers

Implications of the research findings on BIM implementation policy is outlined below:

- There is a need for UK BIM implementation policy makers to promote or mandate certification schemes that cover a broad range of capability criteria including the BIM qualification criteria proposed in this study. This will potentially reduce the laborious nature of pre-qualification and selection exercises as well as the volume of evidence that need to be supplied as part of a principal suppliers CSC BIM capability summary submittals (CPIx forms).

- Standards for BIM implementation and qualification documentation such, as CIC protocol (CIC, 2013a), PAS1192 (2013), PAS 91(2013), must provide more holistic recommended framework for BIM qualification including the indication of criteria importance or priority as established in this study. Notably the CPIx BIM assessment forms in their current state are too complicated and contain too many segments. A more concise assessment form could be developed with a clear indication of assessment criteria priority in various CSC contexts.

10.7.3 Recommendations for Future Research

Implications of the research findings and limitations on future studies are discussed below.

- Future research could adopt entirely qualitative approaches to investigate this phenomenon including the use of case studies or ethnographic studies for more in-depth understanding of the reasons for the relationships identified between BIM qualification (capability) and delivery success. Future quantitative studies may also adopt other statistical modelling techniques, such as Artificial Neural Networks (ANN), in order to compare predictive performance.
- The proposed DSF could also be empirically tested in real life projects for the selection of CSC candidates for projects and compared with other approaches to ascertain its suitability in practical scenario.
- Future research could explore full implementation of the DSF through shareable cloud-based spreadsheets or web-based applications.
- Where resources are available, a wider sample size could be engaged to improve predictive capacity of the quantitative models derived from the multiple regression analysis. This could also be replicated in other locations outside the UK in order to identify distinctions and draw parallels.

10.8 CHAPTER SUMMARY

This chapter has summarised the entire research in relation to attainment of the aim and objectives. This chapter also outlined the contribution of research findings to knowledge, implications for practice as well as limitations. Recommendations were also made to guide future research.

In summary, the research has highlighted the importance of knowledge on the contribution of BIM qualification criteria to BIM delivery success. It has shown that this will enhance pre-qualification and selection decisions; thereby, reducing risk of selecting inappropriate candidates. A practical approach of ensuring this is proposed through a DSF for the CSC.

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APPENDICES

Appendix A: Sample Invitation Letters and Information Sheets

Construction and Property Research Centre
University of the West of England
Bristol
BS16 1QY
United Kingdom
Date…/…/ 2015

Dear Sir/Madame,

REQUEST FOR PARTICIPATION IN RESEARCH ON BUILDING INFORMATION MODELLING (BIM) IN THE CONSTRUCTION SUPPLY CHAIN

The University of the West of England is sponsoring this PhD research into BIM as part of its contribution to the generation of knowledge in the field of construction management. The research aims to deepen the understanding of the relevant criteria and approaches for assessing BIM competence and readiness within UK construction supply chains.

You are cordially invited to contribute your expert knowledge and experience in *an interview/Delphi study/Survey* which will form part of the data collection for this research. Details of the study and requirements for the *interview/Delphi study/Survey* are presented in the attached information sheets.

The study aims to contribute knowledge on the subject area as well as provide recommendations towards overall improvement in the implementation of BIM within construction supply chains.

Your favorable consideration of this request will be much appreciated. Thank you.

Yours sincerely

....

Abdul-Majeed Mahamadu (Doctoral Researcher)

BRISTOL University of the West of England

PARTICIPANT INFORMATION SHEET (Delphi Sample)

Date…/…./ 2015

Project Information

Research: Development of a Decision Support Framework to Aid Selection of Construction Supply Chain Organisations on BIM-Enabled Projects

Aim: The primary aim of this research is to identify and evaluate the criteria necessary for qualifying a supply chain firm (contractors, subcontractors and supplier) to deliver projects through BIM. This will aid the development of a decision support framework to aid the evaluation of supplier's BIM capability during the prequalification and selection phase of projects.

Investigator: Abdul-Majeed Mahamadu (Doctoral Researcher)

Supervisors: Prof. Lamine Mahdjoubi (Director of Studies), Dr Colin Booth

Institution: Construction and Property Research Centre, University of West of England, Bristol, UK

Invitation

You are cordially invited to participate in this research as an expert panelist in a Delphi survey.

Delphi is a structured communication technique for collecting data from experienced or knowledgeable individuals in a particular subject. These experts are required to respond to short questionnaires in two or more rounds. You may therefore be contacted more than twice to contribute to this study**.** After each round an anonymous summary of the responses from the entire group of experts is presented to each participant for consideration before answering the same set of questions in subsequent rounds.

An analysis of the responses is then performed including measurement of statistical agreement between the experts' opinions.

Purpose of Study

The research is strictly for academic purposes and will form part of a thesis report to be submitted in partial fulfilment of the requirements of a PhD study.

Expected Benefits

The framework to be developed will provide evidence-based approach for qualifying prospective supply chain candidates for projects within the UK construction Industry. The framework will be made available to Delphi panellists at the end of the study, upon request.

Procedure

Questionnaires (attached) will be used to solicit your professional and individual opinion about the relevant qualification criteria necessary for assessing a Supply Chain firms' BIM capability during pre-qualification or selection. It is estimated to take between 10-15 minutes.

A summary of the responses will be presented to you after a computation of the statistical mean of each panellist's ratings of the criterions suitability. You will then be required to fill out the same set of questions again after reviewing the summary of responses. This is to aid reduction of the listed BIM qualification criteria to the most relevant. If criteria are considered to be too similar, please provide a favourable response to the most relevant out of the two.

Your Participation and Confidentiality

If you decide to take part, you will be given a consent form to sign agreeing that you understand that information collected will be used for the purpose of research only. Final report will be available for your perusal upon request.

+ Participation is voluntary.
+ There are no anticipated risks or financial implications associated with responding to the questions.
+ The information provided will be considered highly confidential, anonymised. You will be identified by a unique code for the purposes of data analyses. In case you want to withdraw at any point, this will be used to identify your responses. Your real identity will not be exposed to any other person except the researcher and supervision team.
+ No response shall be considered wrong.

- Any voice recordings may be made for subsequent transcription and analysis. Audios will, however, be deleted at the end of the study.

Context and Definitions

It will be appreciated if all your responses are specifically based on your experience and knowledge about BIM in the context of construction Supply Chains.

For the purpose of this study you may rely on the following definitions.

Construction Supply Chain Firm: Any organisation that delivers service at any point in a project's lifecycle.

Qualification Criteria: An attribute related to a Supply Chain firm that can be objectively measured and represent an ability to generate BIM deliverables and services.

Thank you for considering participation in this research project.

Abdul-Majeed Mahamadu(Investigator) Doctoral Researcher Construction and Property Research Centre University of the West of England Frenchay Campus Coldharbour Lane Bristol. UK BS16 1QY Tel: +44 (0)117 32 83902	*This research is being supervised by Prof. Lamine Mahdjoubi and Dr Colin Booth. The research team has extensive knowledge in the ethical conduct of research that requires confidential expert opinion such as this Delphi study.* *Do not hesitate to contact any of the team members for further clarification.*

University of the West of England
BRISTOL

PARTICIPANT CONSENT FORM (Delphi sample)

I confirm that I have read and understood the *Information Sheet* for the above study, and have had the opportunity to ask questions. □

I understand that participation is voluntary and that I may withdraw at any time, without giving any reason for doing so. □

I understand that my identity will never be revealed to anyone except to researcher and supervision team. □

I understand the reason for this study and agree to participate. □

Participant Name: ……………………………………………………………………………

Participant Signature: ……………………………………..……………………………

Date: ……………………………………………………………………………………………..

Principal Investigator Signature: ……………………………………………………..

Date: ………………………………………………………………………..……………………..

PLS KEEP ONE COPY AND RETURN COPY TO RESEARCHER

Appendix B: Interview Protocol

Section A: *Introduction*
1. Please provide a brief profile of your current position within your organisation, nature and size of business, experience within the construction industry. 2. Please outline how your role is related to BIM or the Supply Chain of projects that you are involved with.
Section B: *Importance of BIM Qualification*
1. What are the primary objectives of evaluating BIM capability of a firm during pre-qualification or selection? 2. How do you currently perform evaluations and how could it be improved? 3. Are you aware of any existing guidance documents, frameworks or tools for such evaluations? *(e.i. iCMM ; BIMMi; CIC; CIFE Scorecard; BIM Quickscan etc.)* a. Do they suit the requirements of pre-qualification or selection? b. How can they be improved? 4. Do standards such as the PAS 1192 AND CIC Protocol provide any guidance on this and how? 5. Are there any other publicly available frameworks or guidance that could be helpful?
Section C: *Determining Criteria for Assessing the Ability to Deliver BIM*
1. In your opinion, how do the following aspects of an organisation affect BIM capability, maturity and competence? a. Company Attributes and Characteristics. b. Situational or Environmental Attributes and Characteristics. 2. In your opinion how should they be assessed during prequalification or selection of the supply chain? 3. Please propose/list a set of criteria you find most useful for qualifying a supply chain firm for a BIM-enabled project? 4. In your opinion, how do supply chain perceptions, attitudes or acceptance affect their readiness for BIM? Can this be objectively measured? 5. What other attributes of an organisation could serve as an objective measure?

Appendix C: Sample Delphi Survey Questionnaire

Please tick (click) appropriate box (example ☑ or ◉) or type responses where appropriate. Please indicate the extent to which you agree with the suitability of the listed criteria for assessing supply chain (Contractors/ Consultants/Subcontractors/Suppliers) firm's ability to deliver through BIM on projects. List of abbreviations is provided on page 5

Background	
Email / Delphi Panel ID	
Profession/Job Title	
Qualification	HNC/HND □ Bachelor's Degree □ Master's Degree □ Doctorate Degree □ Other □ ………………………………………..
Professional Body Membership	
Years of Experience - Construction Industry	
Years of Experience - Usage of BIM /Virtual Digital Construction (VDC) Technology	
Years of Experience - Tendering, Pre-qualification and Selection	

1. **To what extent do you agree that the following criteria are used in assessing BIM competence and readiness during tender (selection) or pre-qualification?**

C1 Proposed ***competence*** related assessment criteria	**Strongly Agree**	**Agree**	**Neutral**	**Disagree**	**Strongly Disagree**
Managerial staff BIM qualification *(e.g. certificates, degrees etc.)*	□	□	□	□	□
Key technical staff BIM qualification *(e.g. certificates, degrees etc.)*	□	□	□	□	□
Staff training and continuous professional development- CPD *(e.g. total number/ hours)*	□	□	□	□	□
Managerial staff BIM experience	□	□	□	□	□
Key technical staff BIM experience	□	□	□	□	□
BIM staff availability for project *(e.g. % of time /number to be allocated to project)*	□	□	□	□	□
Organisation accreditations and certifications *(e.g. licences, certificates accreditations)*	□	□	□	□	□
Organisations BIM training arrangements *(e.g. BIM/VDC training budget/plans)*	□	□	□	□	□
BIM software experience *(e.g. no. of years usage of relevant software)*	□	□	□	□	□

Past BIM project experience *(e.g. number/value of projects)*	□	□	□	□	□
BIM experience on similar project *(e.g. number/value of projects)*	□	□	□	□	□
Collaborative (project) procurement experience *(e.g. number/value of Frameworks, Partnering, IPD DB etc.)*	□	□	□	□	□
Internal use collaborative IT systems *(e.g. usage-extranet, intranet, collaborative tools etc.)*	□	□	□	□	□

C2 Proposed ***capacity and resources*** related assessment criteria	**Strongly Agree**	**Agree**	**Neutral**	**Disagree**	**Strongly Disagree**
IT vision and mission *(e.g. evidence it supports company key objectives)*	□	□	□	□	□
BIM vision and mission *(e.g. evidence it supports company key objectives)*	□	□	□	□	□
Quality of BIM implementation strategy within firm *(e.g. evidence it's based on best practice PAS, ISO , CIC etc.)*	□	□	□	□	□
Change management maturity (*e.g. evidence of successful implementation of change in the past)*	□	□	□	□	□
IT budget *(e.g. % of total budget)*	□	□	□	□	□
IT Training budget (e.g. *% of total training budget)*	□	□	□	□	□
Hardware availability for project *(e.g. PC's capacity or workstation specifications*)	□	□	□	□	□
Hardware – state-of-the-art *(i.e. availability of most up to date versions of hardware/workstations)*	□	□	□	□	□
Software availability *(i.e. availability/ suitability of software)*	□	□	□	□	□
Suitability of data storage arrangements/capacity (e.g. *cloud storage solutions availability etc.*)	□	□	□	□	□
Network infrastructure *(i.e. availability of network infrastructure to support BIM)*	□	□	□	□	□
SPECIFIC BIM MODELLING CAPABILITY AND PROPOSED METHOD					
Internal information standards *(e.g. best practice e.g. ISO , PAS, quality plans etc.)*	□	□	□	□	□
BIM standards *(e.g. extent of compliance or reliance on best practice etc.)*	□	□	□	□	□
BIM research and development *(e.g. programmes or % of total budget/budget ratio etc.)*	□	□	□	□	□
Data classification or naming practices *(e.g. experience using UNICLASS, PAS etc.)*	□	□	□	□	□
BIM Coverage capacity *(e.g. expertise - life cycle views -2D, 3D, 4D, 5D, 6D, ND)*	□	□	□	□	□
BIM Model maturity capacity *(e.g. expertise BIM maturity level e.g. level 1,2 or 3)*	□	□	□	□	□
Model LOD/LOI capacity *(e.g. expertise in modelling to appropriate LOD/LOI)*	□	□	□	□	□
Model server usage *(i.e. availability and use)*	□	□	□	□	□

Suitability of proposed plan for BIM service *(e.g. extent meets project or employers BIM requirement i.e. BEP meets EIR)*	◻	◻	◻	◻	◻
Innovativeness of proposed plan for BIM service *(e.g. uniqueness of proposed BIM plan in meeting employers requirement i.e. BEP meets EIR)*	◻	◻	◻	◻	◻
Vendor involvement and support *(e.g. evidence of after sales support from BIM vendors)*	◻	◻	◻	◻	◻
Suitability of privacy and security proposals *(e.g. extent of compliance or reliance on best practice)*	◻	◻	◻	◻	◻

C3 Proposed ***culture and attitude*** related assessment criteria	**Strongly Agree**	**Agree**	**Neutral**	**Disagree**	**Strongly Disagree**
Reputation in BIM- Past BIM project performance *(e.g. recommendations and testimonials)*	◻	◻	◻	◻	◻
Past relationship with principle supplier/client *(e.g. reliability, collaboration, performance etc.)*	◻	◻	◻	◻	◻
Technology readiness (attitude towards new technology/willingness)	◻	◻	◻	◻	◻
Youthfulness of staff *(e.g. % of employees less than 30 years of age)*	◻	◻	◻	◻	◻
Number of graduates in firm *(e.g. % of employees qualified above HND)*	◻	◻	◻	◻	◻
Awareness/knowledge of BIM benefits in project context	◻	◻	◻	◻	◻
Extent of IT support to core business/processes *(e.g. % of total output in digital format e.g. drawings, BOQ's issued)*	◻	◻	◻	◻	◻
Organisational structure –Level of Decentralisation *(e.g. evidence of decentralised decision making)*	◻	◻	◻	◻	◻

C4 Proposed ***cost*** related criteria	**Strongly Agree**	**Agree**	**Neutral**	**Disagree**	**Strongly Disagree**
Price/Cost for delivering BIM	◻	◻	◻	◻	◻

Please provide comments, additional criteria or measures

………

Please return or direct any enquiries to:
University of the West of England
Frenchay Campus
Bristol, UK
BS16 1QY

Appendix D: Sample General Survey Questionnaire

Dear Participant,

This survey is being conducted as part of a PhD study on BIM use for the construction Supply Chain. The survey aims to establish the impact of BIM qualification criteria on delivery success. It seeks to establish the extent to which organisational attributes related to their BIM capability impact on the successful delivery of BIM.

The survey will take 12-15 minutes. I would appreciate your participation.

All information collected will be analysed securely. Individual participants will never be identified at any point of this study.

All information about this study is contained in the attached information sheet. If you have any further questions about this survey or the research please, do not hesitate to contact me.

Please return or direct any enquiries to:
Abdul-Majeed Mahamadu |Doctoral Researcher |University of the West of England | Bristol, UK | BS16 1QY| Email: abdul.mahamadu@uwe.ac.uk

Survey Instructions

- *Please, answer the remaining questions in relation to your experience, knowledge or association with BIM use by an organisation on a past or ongoing project*
- *Supply Chain as used in this survey refers to any organisation that participates in the project delivery process (This includes: Main Contractor; Sub Contractor; Design Consultants (Architects, Engineers etc.); Other Consultant (Cost, QS etc.); Material Suppliers etc.)*

1. Background Information

1. Which of the following best describes your profession	☐ **Architect**	☐ **Engineer**	☐ **Quantity Surveyor**
	☐ BIM Manager/Tech	☐ Project Manager	☐ Academic
	☐ BIM Vendor	☐ Other	
2. Experience - Construction Industry	☐ 1-5 years	☐ 6-10 years	☐ 11-15 years
	☐ Over 15 years		
3. Experience - BIM or Virtual Digital Construction (VDC) Technology	☐ 1-3 years	☐ 4-6 years	☐ 7-10 years
	☐ Over 10 years		
4. Your Qualification	☐ GCSCE/ A-level	☐ HND	☐ Bachelor's Degree
	☐ Master's Degree	☐ Doctorate	☐ Other

2. *Please answer the remaining questions with reference to a specific construction organisation on a specific BIM project.*
   The questions require a description of characteristics of this organisation as well as your assessment of criteria you believe impacted their BIM delivery success.

1. Which of the following best describes the organisation **(If *University Research/Case Study* you may choose an additional answer)**	☐ **Client**	☐ **Main Contractor**	☐ **Sub Contractor**
	☐ Design Consultant (Arc.)	☐ Material Supplier	☐ University Research/Case Study
	☐ Design Consultant (Engineering)	☐ Other Consultant	☐ Other
2. Are you employed by the organisation	☐ Yes	☐ No	
3. Size of firm (no. employees)	☐ Less than 50	☐ 50-250	☐ Over 250
4. Firm's general experience	☐ Less than 5 years	☐ 5-10 years	☐ 11-15 years
	☐ 16-20 years	☐ Over 20 years	
5. Firm's BIM or Virtual Digital Technology experience	☐ Less than 3 years	☐ 3-6 years	☐ 7-10 years
	☐ 11-14 years	☐ 15 years and over	
6. Which of the following best describes the position of this firm in a typical construction supply chain	☐ Top Tier (firms in direct contract with client)	☐ Middle Tier (firms contracted by top tier)	☐ Lower Tier (firms contracted by middle tier)

The following attributes may contribute to the successful delivery of BIM. *3. Please answer with reference to the construction organisation described above!* Please rate the extent to which you feel the outlined attributes influenced (+positively) this organisation's BIM delivery success (or performance)?		No Influential at all	Slightly Influential	Quite Influential	Very Influential	Extremely Influential
Professional and Academic Qualifications	Key technical staff BIM qualification	☐	☐	☐	☐	☐
	BIM staff availability for project	☐	☐	☐	☐	☐
	Organisation's BIM accreditations and certifications	☐	☐	☐	☐	☐
	Organisation's BIM training arrangements	☐	☐	☐	☐	☐
Staff Experience	Managerial staff BIM experience	☐	☐	☐	☐	☐
	Key technical staff experience	☐	☐	☐	☐	☐
Organisation's Experience	BIM software experience	☐	☐	☐	☐	☐
	Past BIM project experience	☐	☐	☐	☐	☐
	BIM experience on similar project	☐	☐	☐	☐	☐
	Internal use collaborative IT systems	☐	☐	☐	☐	☐
Administrative and Strategic Capacity	IT vision and mission	☐	☐	☐	☐	☐
	Quality of BIM implementation Strategy/Plans	☐	☐	☐	☐	☐
	BIM research and development	☐	☐	☐	☐	☐
Technical (Physical) Resources	Software available to firm	☐	☐	☐	☐	☐
	Data storage (arrangements/capacity) within firm	☐	☐	☐	☐	☐
	Firms' network infrastructure	☐	☐	☐	☐	☐
Specific BIM Modelling Capacity	BIM Standards (compliance with best practice)	☐	☐	☐	☐	☐
	Data classification/naming practices	☐	☐	☐	☐	☐
	Model maturity capacity	☐	☐	☐	☐	☐
	Model LOD/LOI capacity	☐	☐	☐	☐	☐
Method of Suitability	Suitability of proposed BEP in meeting project EIR	☐	☐	☐	☐	☐
	BIM software vendor involvement and support for project	☐	☐	☐	☐	☐
Reputation	Reputation of firm in BIM - Past Performance	☐	☐	☐	☐	☐
Technology Readiness	Technology Readiness (attitudes towards new technology)	☐	☐	☐	☐	☐
	Awareness of BIM benefits (in project context)	☐	☐	☐	☐	☐
	Extent of IT support to core business or processes within firm	☐	☐	☐	☐	☐
Organisational Structure	High level of decentralisation	☐	☐	☐	☐	☐
Cost	Higher cost and prices charged for BIM services	☐	☐	☐	☐	☐

The following are critical success areas in the delivery of BIM. 4. Please express your satisfaction with the extent to which the following objectives have been met on the project referred to above?	Not at all	Poor	Fair	Good	Very Good	Excellently
Attainment of BIM model **quality** (accuracy, usability and conformance to requirements)	☐	☐	☐	☐	☐	☐
Attainment of BIM deliverables on **schedule** (timely)	☐	☐	☐	☐	☐	☐
Attainment of BIM deliverables **within budget** (cost)	☐	☐	☐	☐	☐	☐
Inter organisational **collaboration**	☐	☐	☐	☐	☐	☐
Effective **coordination** with other Supply Chain (project teams) through BIM	☐	☐	☐	☐	☐	☐
Effective **integration** of the Supply Chain (project teams) through BIM	☐	☐	☐	☐	☐	☐

5. A. Please describe the project being assessed

Please tick only one answer

1. Size (value) of Project	☐ Less than £25M	☐ £26M to £50M	☐ £51 to £75M
	☐ £76M to £ 100M	☐ Over £100M	
2. Project Supply Chain (organisational) complexity	☐ Highly Fragmented	☐ Some Fragmentation	☐ Intermediate
	☐ Fairly Integrated	☐ Fully Integrated	
3. Extent of Supply Chain involvement in BIM process	☐ Only Top Tier Participation	☐ Some Middle Tier Participation	☐ Significant Middle Tier Participation
	☐ Lower Tier Participation	☐ Entire Supply Chain Participation	

5. B. Project information *Please tick only one answer*	Very Low	Low	Average/Intermediate	High	Very High
1. Complexity of product (building/facility) modelled on this project	☐	☐	☐	☐	☐
2. Maturity level of project BIM (Level 1 to 3)	☐	☐	☐	☐	☐
3. BIM Complexity (LOD/Model uses/2D to nD etc.)	☐	☐	☐	☐	☐
4. Level of firm's BIM task/ design responsibility on project	☐	☐	☐	☐	☐

Appendix E: Sample Validation Feedback Form

INTRODUCTION

With the emergence of Building Information Modelling (BIM), a critical criterion for selecting Construction Supply Chain (CSC) organisations for projects is the ability to deliver BIM. Despite emerging research on BIM capability, there are very few studies specifically looking at qualification of CSC firms for projects. Furthermore, there are no studies that have empirically analysed the critical BIM qualification criteria impacting on the level of attainment of BIM delivery success.

Aim of Research

This research was conducted to identify critical BIM qualification criteria as well as investigate their impact on BIM delivery success. A Decision Support Framework (DSF) for predicting the likelihood of success by CSC firms is proposed from the research findings. This is proposed to aide evidence based decision making in the selection of candidates for BIM-enabled projects.

RESEARCH METHOD

A mixed methodological research strategy was adopted for the study. After an extensive literature review, semi-structured interviews (n=8) were used to solicit expert opinion on appropriate qualification criteria for BIM. This was followed by a Delphi Survey (n=25) of construction professionals with extensive CSC or BIM procurement experience to identify the most critical of the proposed qualification criteria. The contribution of the qualification criteria to BIM delivery success was then determined through a survey of 64 (i.e. n=64) CSC firms on BIM-enabled projects within UK.

KEY RESEARCH TERMS

Construction Supply Chain (CSC): This represents any organisation in the construction delivery process. The CSC organisations surveyed in this study were: *main contractors, sub-contractors, design consultants (architects), design consultants (engineering) and material suppliers.*

BIM Qualification Criteria: Represents an attribute of an organisation that can be assessed as evidence of their ability to deliver BIM.

FINDINGS

A summary of the key findings from the research have been presented subsequent pages.

Feedback

Please provide comments on how valid the research findings are with regards to your experience with using or implementing BIM within the U.K.

Pleas provide a few details

Background Information	
Professional/Job Title	
Qualification and Professional Membership	
Years of Experience General	
Years of Experience BIM/VDC	

Key Finding 1

- 11 critical BIM qualification criteria were identified consisting of 28 sub-criteria across 4 distinctive areas of assessment. This is presented in **Table 1**.

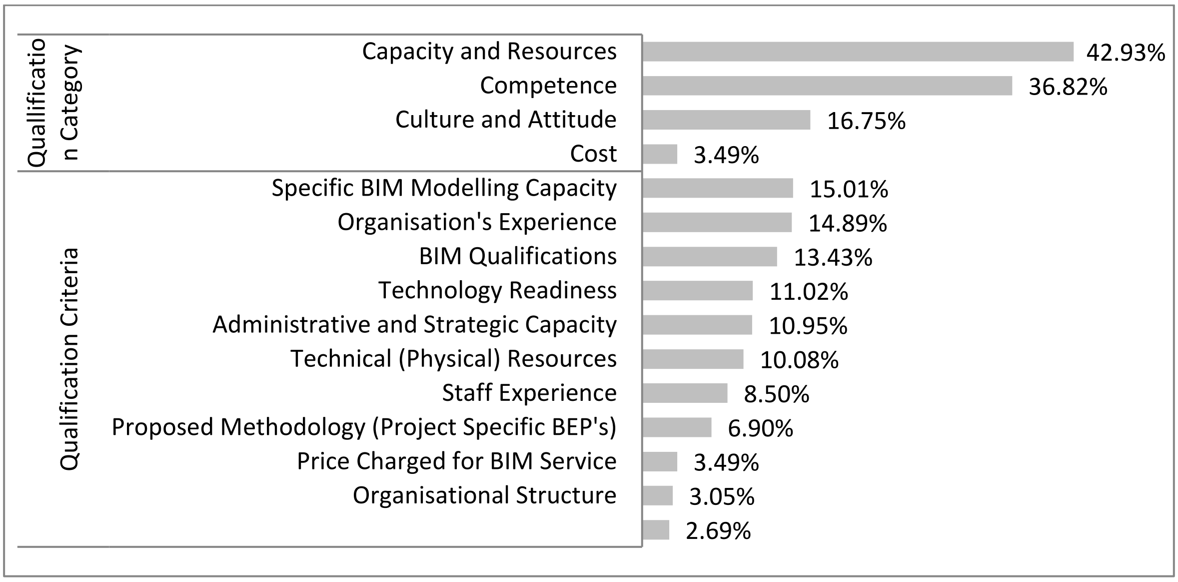
List of the Most Critical BIM Qualification Criteria

Qualification Criteria		Description/Sub-Criteria
Competence	Professional and Academic Qualifications	Key technical staff BIM qualification; BIM staff availability for project ; Organisation's BIM accreditations and certifications; and Organisation's BIM training arrangements
	Staff Experience	Managerial staff BIM experience; and Key technical staff experience
	Organisation's Experience	BIM software experience; Past BIM project experience; BIM experience on similar project; and Internal use collaborative IT systems
Capacity and Resources	Administrative and Strategic Capacity	IT vision and mission; Quality of BIM implementation Strategy/Plans; and BIM research and development
	Technical (Physical) Resources	Software available to firm; Data storage (arrangements/capacity) within firm; and Firms' network infrastructure
	Specific BIM Modelling Capacity	BIM Standards (compliance with best practice); Data classification/naming practices; Model maturity expertise; and Model LOD/LOI expertise
	Proposed Method of BIM Delivery	Suitability of proposed BEP in meeting project EIR; and BIM software vendor involvement and support for project
Culture and Attitude	Reputation	Reputation of firm in BIM - Past Performance
	Technology Readiness	Technology Readiness (attitudes towards new technology); Awareness of BIM benefits (in project context); and Extent of IT support to core business or processes within firm
	Organisational Structure	Organisational structure (levels of decentralisation)
Cost		Prices charged for BIM services

Respond to the question below by checking [×] one of the multiple choice options and also by providing your comments.	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
Key Research Findings					
The criteria identified are relevant to BIM qualification of CSC organisations during selection or pre-qualification.	☐	☐	☐	☐	☐
The criteria identified are adequate for BIM qualification of CSC organisations during selection or pre-qualification.	☐	☐	☐	☐	☐

- **Key Finding 2**

The following **Figure (1)** shows the extent to which BIM qualification criteria contributed to the overall delivery success on 64 projects investigated in the UK.



Influence of Qualification (capability) Criteria on Overall BIM Delivery Success

Capacity related 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 Sub-criteria with the highest weighted contribution was Specific BIM Modelling Capacity with overall contribution of 15.01% followed by Organisations Experience (14.89%). The other High Contributors were Professional and Academic Qualifications (13.43%) and Technology Readiness (11.02%).

Please refer to table 1 for details about each criterion

Respond to the question below by checking [×] one of the multiple choice options and also by providing your comments.	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
Key Research Findings					
The relative contribution of criteria to overall delivery success is presented in Figure 1 above. To what extent do you agree with this finding?	☐	☐	☐	☐	☐

➢ **Key Finding 3**

The highlighted criteria were identified as the most influential in the attainment of success in some specific areas as detailed in Table 2.

Influence of BIM Qualification Criteria on Specific Areas of Delivery Success

Areas of Success Assessed		**Most Influential Criteria**
BIM Modelling Success	Model Quality	Staff Experience and Proposed Method of BIM Delivery (Suitability of Project BEP's)
	Delivery of BIM on schedule	
	Delivery of BIM within budget	
Supply Chain Success through BIM	Collaboration	Administrative and Strategic Capacity (NB: *Administrative and Strategic Capacity* was most influential on CSC success on projects with complex supply chains)
	Coordination of CSC	
	Integration of CSC	

The results above determined through multiple regression analysis. It shows that *staff experience* and *proposed method for* delivery of BIM on projects are the most influential to BIM modelling success (quality of BIM models, delivery of BIM within schedule and cost). It was also found that project complexity characteristics (such as size and complex designs) did not affect the attainment of BIM modelling success.

On the other hand, the *administrative and strategic capacity* of CSC was the most critical to the supply chain success with specific reference to strategic supply chain management (SCM) objectives such as collaboration, coordination and integration of CSC through BIM. BIM was also found to support the delivery of key SCM objectives mostly on projects with a complex CSC.

Respond to the questions below by checking [×] one of the multiple choice options and also by providing your comments.	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
Key Research Findings					
To what extent do you agree with the findings about the most significant contributors to BIM Modelling success (i.e. model quality, delivery of models on schedule and within budget)?	☐	☐	☐	☐	☐
To what extent do you agree with the findings about the most significant contributors to supply chain success through BIM (i.e. collaboration, coordination and integration)?	☐	☐	☐	☐	☐

Respond to the questions below by checking [×] one of the multiple choice options and also by providing your comments.	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
Key Research Findings					
BIM was found to support CSC success mostly on projects with a complex CSC. To what extent do you agree with the findings?	☐	☐	☐	☐	☐
BIM modelling quality, delivery of BIM on schedule and within cost is not dependent of project complexity. To what extent do you agree with the findings?	☐	☐	☐	☐	☐

A Consolidation of the Research Findings: A Decision Support Framework to Enable Selection of Supply Chain Organisations for Projects

A decision support framework was developed from the research findings. The coefficients from the statistical analysis were converted into weights and applied to this framework for prediction of delivery success. Criteria description and rating guidance scale have also been developed from research discussions and literature. This framework will guide the evaluation potential CSC for projects in order to select best candidate. The best candidate will be determined based weighted aggregation of performance in each qualification area. Please find framework in attached document for your perusal.

Please provide comments on how valid the research findings are with regards to your experience. Respond to the questions below by checking [×] one of the multiple choice options and also by providing your comments.	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
The attached framework provides useful and relevant information for the qualification of CSC organisations for projects.	☐	☐	☐	☐	☐
The attached descriptions and rating scales are very relevant to CSC pre-qualification or selection of CSC for projects.	☐	☐	☐	☐	☐
Comments *Please provide any additional comments about the validity of the findings or the relevance of the framework.*					

Appendix F: Research Statistics

Appendix F1 – Variables for Construction of Composite Index of Variables

	Research Variable (index)	Constituent Items	Weighting *W* (%)	Research Use
BIM Qualification Criteria	Qualification (4 Items)	Key Technical Staff BIM Qualification	23.95	Investigate impact on attainment of success
		BIM Staff Availability for Project	27.26	
		Organisation's BIM Accreditations and Certifications	19.49	
		Organisation's BIM Training	29.30	
	Staff Experience (2 items)	Managerial Staff BIM Experience	45.88	
		Key Technical Staff BIM Experience	54.12	
	Organisation Experience (4 Items)	BIM Software Experience	26.90	
		Past BIM Project Experience	26.44	
		BIM Experience on Similar Project	22.18	
		Internal Use of Collaborative IT Systems	24.48	
	Administrative and Strategic Capacity (3 Items)	IT Vision and Mission	31.56	
		Quality of BIM Implementation Strategy	35.94	
		BIM Research and Development	32.50	
	Technical (Physical) Resources (3 Items)	Software Availability	38.03	
		Data Storage (suitability and capacity)	30.73	
		Network Infrastructure	31.24	
	Specific BIM Modelling Capacity (4 Items)	BIM Standards	26.45	
		Data Classification and Naming Practices	25.54	
		Model Maturity Expertise/Capacity	21.09	
		Model LOD/LOI Expertise/Capacity	26.91	
	Proposed Methodology (2 Items)	Suitability of Proposed BIM Execution Plans for Project	61.04	
		BIM Vendor Involvement and Support	38.96	
	Reputation	Reputation – Past Performance on BIM Projects	100.00	
	Technology Readiness (3 Items)	Attitude and Willingness	33.39	
		Awareness of BIM Benefits	37.11	
		Extent of IT Support to Core Business/Processes	29.50	
	Organisational Structure	Organisational Structure – Level of Decentralisation	100.00	
	Cost	Cost/Price of BIM Service	100.00	
Delivery Success	Overall BIM Delivery Success (3 Items)	Quality of BIM Deliverables	33.33	Identify influence of qualification criteria
		BIM Delivery on Schedule	33.33	
		BIM Delivery Within Budget	33.33	
	Overall Supply Chain Success through BIM (3 Items)	Collaboration of Supply Chain through BIM	33.33	
		Coordination of Supply Chain through BIM	33.33	
		Integration of supply Chain through BIM	33.33	
Project Complexity Characteristics	Project BIM Complexity (3 Items)	Product or Facility Complexity (design)	33.33	Identify mediation or moderation effect on attainment of success
		Project BIM Model Complexity	33.33	
		BIM Task responsibility of CSC organisation	33.33	
	Project –Supply Chain Complexity (2 Items)	Level of Supply Chain Integration	50.00	
		Supply Chain Involvement in BIM Process	50.00	
	Project Size		100.00	

Appendix F2 – Details on Regression Analysis

- **Regression Model Summary - BIM Modelling Success**

Model Summary[e]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics					Durbin-Watson
					R Square Change	F Change	df1	df2	Sig. F Change	
1	.520[a]	.270	.259	.76413	.270	22.982	1	62	.000	
2	.597[b]	.356	.335	.72363	.086	8.135	1	61	.006	
3	.636[c]	.405	.375	.70148	.049	4.912	1	60	.030	
4	.616[d]	.379	.359	.71064	-.026	2.602	1	60	.112	1.383

a. Predictors: (Constant), Index_Qual

b. Predictors: (Constant), Index_Qual, index_Staff_Exp

c. Predictors: (Constant), Index_Qual, index_Staff_Exp, Index_Meth_Suita

d. Predictors: (Constant), index_Staff_Exp, Index_Meth_Suita

e. Dependent Variable: IndexSuccess

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	13.419	1	13.419	22.982	.000[b]
	Residual	36.202	62	.584		
	Total	49.621	63			
2	Regression	17.679	2	8.839	16.881	.000[c]
	Residual	31.942	61	.524		
	Total	49.621	63			
3	Regression	20.096	3	6.699	13.613	.000[d]
	Residual	29.525	60	.492		
	Total	49.621	63			
4	Regression	18.816	2	9.408	18.629	.000[e]
	Residual	30.805	61	.505		
	Total	49.621	63			

a. Dependent Variable: IndexSuccess

b. Predictors: (Constant), Index_Qual

c. Predictors: (Constant), Index_Qual, index_Staff_Exp

d. Predictors: (Constant), Index_Qual, index_Staff_Exp, Index_Meth_Suita

e. Predictors: (Constant), index_Staff_Exp, Index_Meth_Suita

- **Regression Model Summary – Construction Supply Chain Success through BIM**

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics					Durbin-Watson
					R Square Change	F Change	df1	df2	Sig. F Change	
1	.507[a]	.257	.245	.78138	.257	21.489	1	62	.000	2.059

a. Predictors: (Constant), Index_Admin_Strat

b. Dependent Variable: IndexSCSuccess

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	13.120	1	13.120	21.489	.000[b]
	Residual	37.855	62	.611		
	Total	50.975	63			

a. Dependent Variable: IndexSCSuccess

b. Predictors: (Constant), Index_Admin_Strat

- **Mediation Regression Model Summary - BIM Modelling Success**

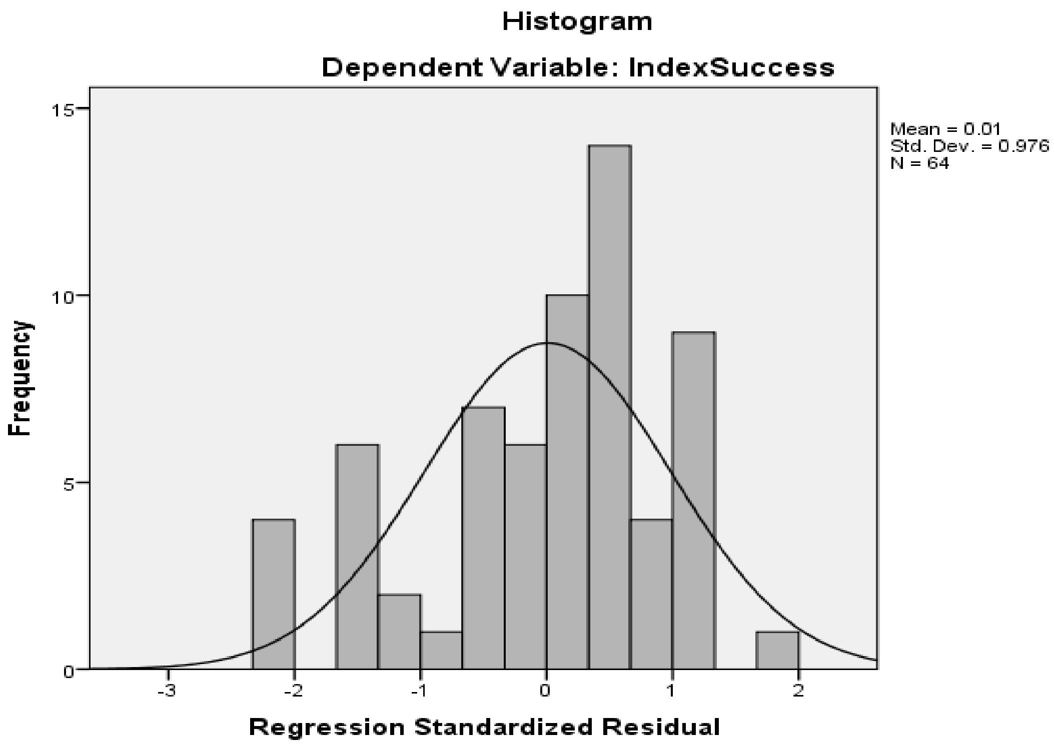
Model Summary[c]

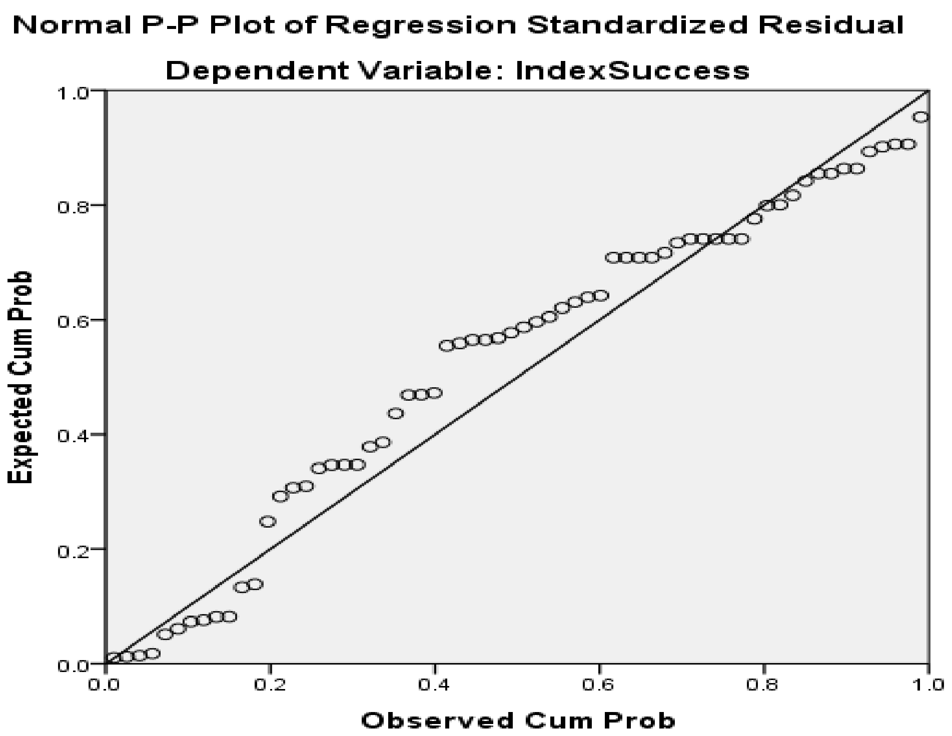
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics					Durbin-Watson
					R Square Change	F Change	df1	df2	Sig. F Change	
1	.529[a]	.280	.268	.77127	.280	23.315	1	60	.000	
2	.623[b]	.388	.368	.71684	.108	10.457	1	59	.002	1.373

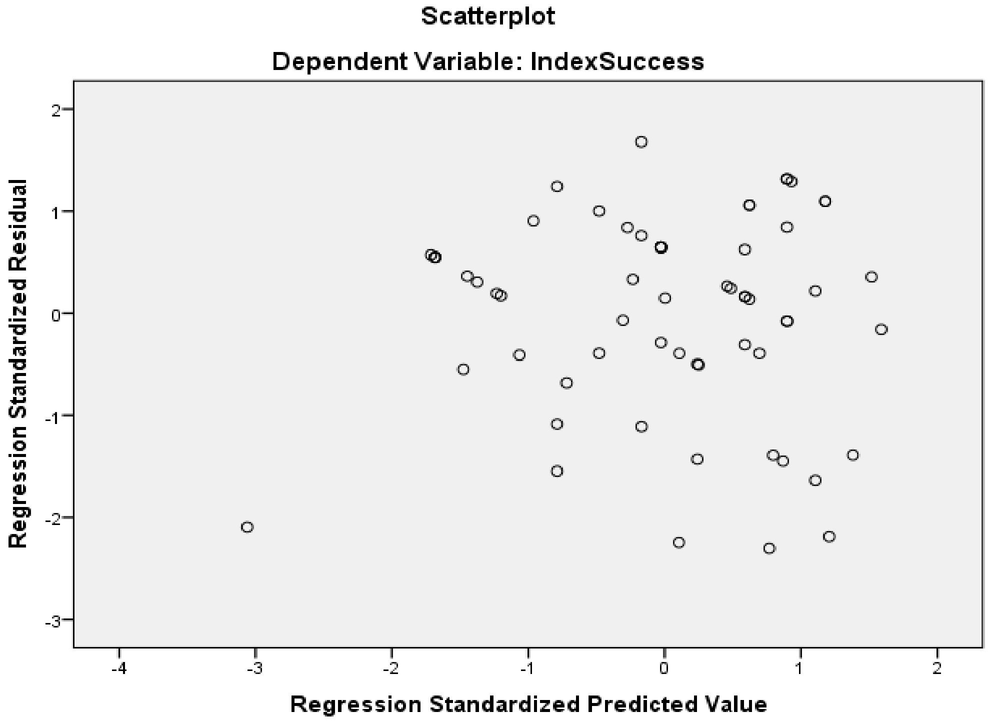
a. Predictors: (Constant), index_Staff_Exp

b. Predictors: (Constant), index_Staff_Exp, Index_Meth_Suita

c. Dependent Variable: IndexSuccess


Histogram
Dependent Variable: IndexSuccess
Mean = 0.01
Std. Dev. = 0.976
N = 64
Frequency
15
10
5
0
-3
-2
-1
0
1
2
Regression Standardized Residual


Normal P-P Plot of Regression Standardized Residual
Dependent Variable: IndexSuccess
Expected Cum Prob
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
Observed Cum Prob



- **Mediation Regression Model Summary – Construction Supply Chain Success through BIM**

Model Summary[d]

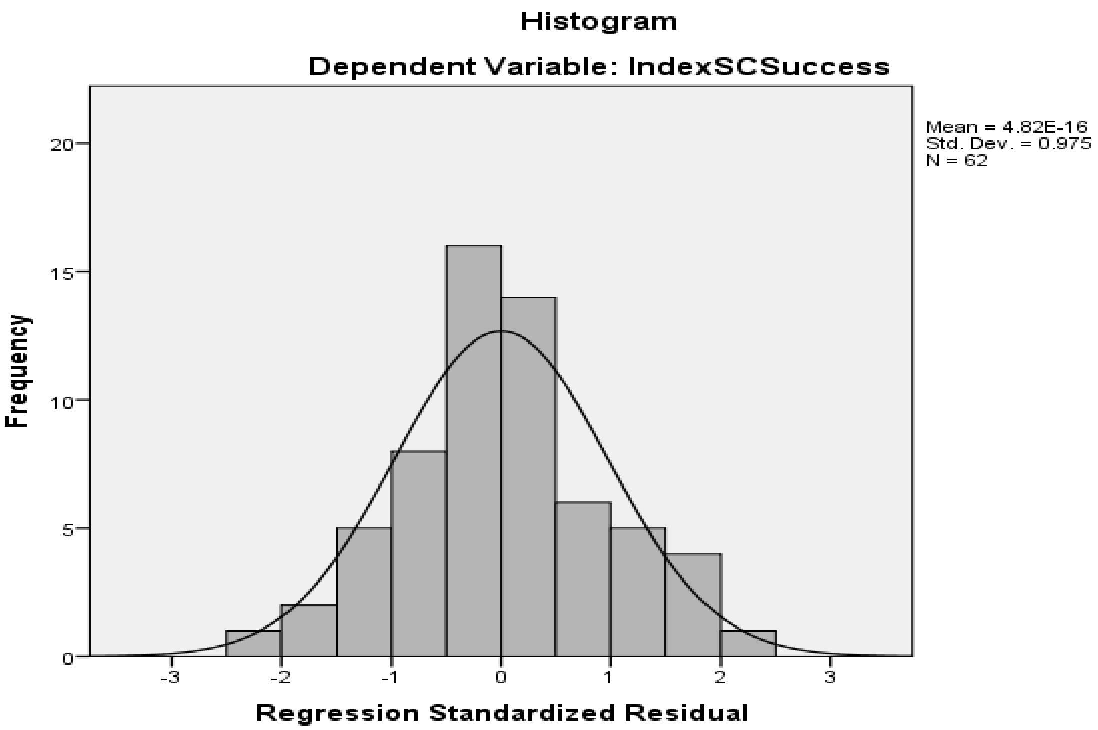
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics					Durbin-Watson
					R Square Change	F Change	df1	df2	Sig. F Change	
1	.491[a]	.242	.229	.78495	.242	19.108	1	60	.000	
2	.569[b]	.323	.300	.74774	.082	7.121	1	59	.010	
3	.607[c]	.368	.335	.72872	.045	4.120	1	58	.047	2.174

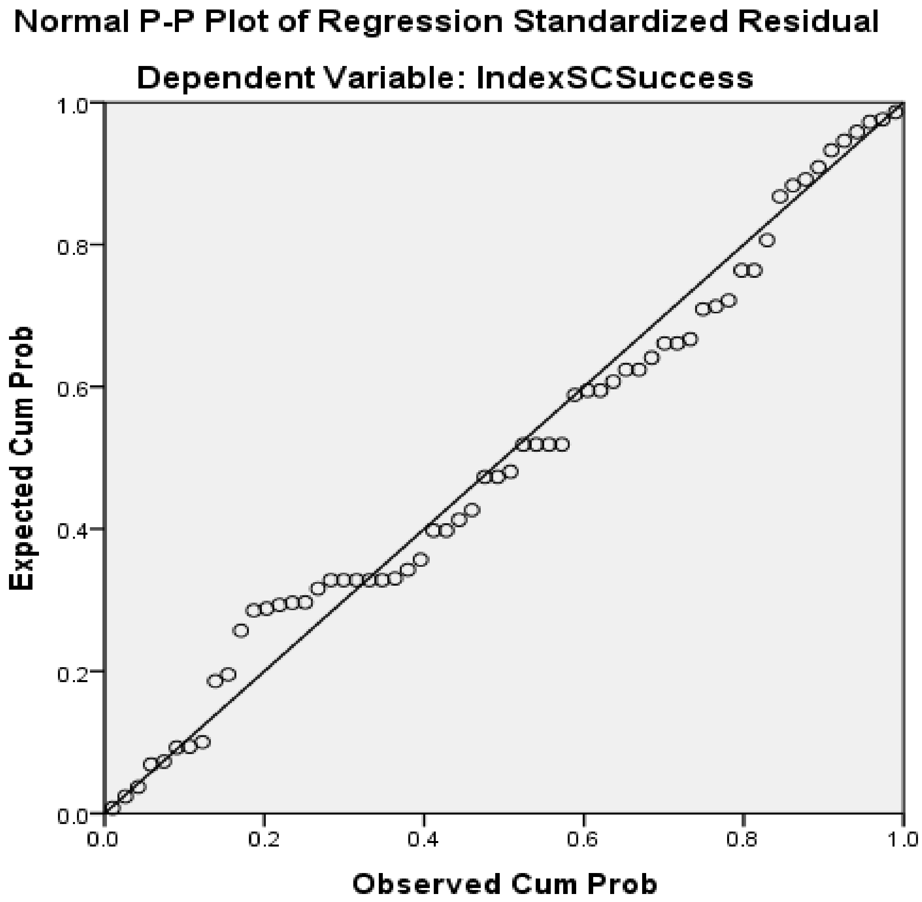
a. Predictors: (Constant), Index_Admin_Strat

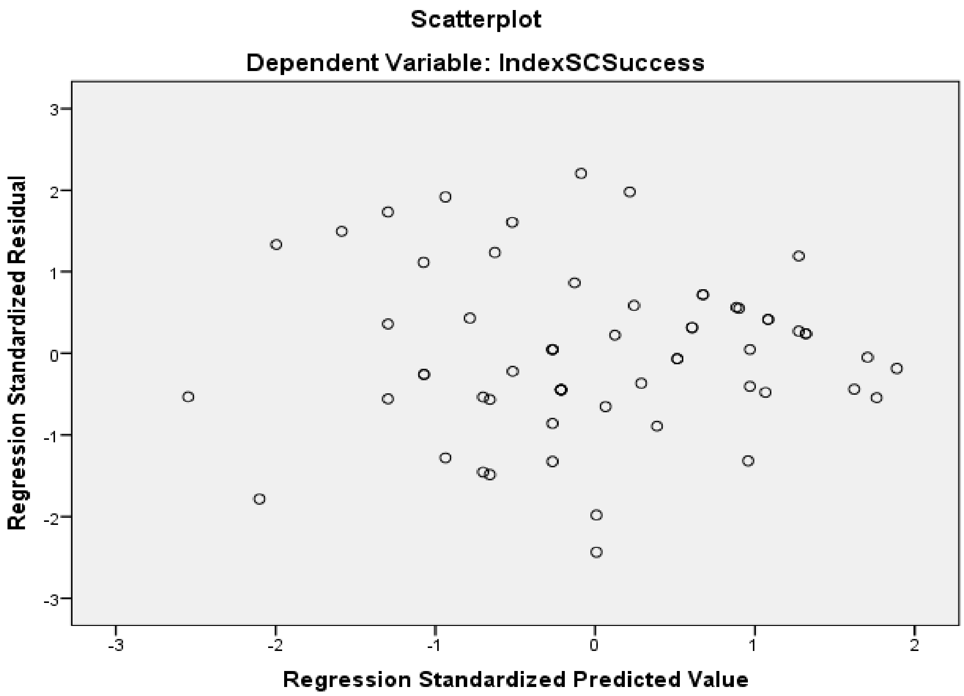
b. Predictors: (Constant), Index_Admin_Strat, Index_SCComp

c. Predictors: (Constant), Index_Admin_Strat, Index_SCComp,

d. Dependent Variable: IndexSCSuccess


Histogram
Dependent Variable: IndexSCSuccess
Mean = 4.82E-16
Std. Dev. = 0.975
N = 62
Frequency
Regression Standardized Residual


Normal P-P Plot of Regression Standardized Residual
Dependent Variable: IndexSCSuccess
Expected Cum Prob
Observed Cum Prob


Scatterplot
Dependent Variable: IndexSCSuccess
Regression Standardized Residual
Regression Standardized Predicted Value
3
2
1
0
-1
-2
-3
-3
-2
-1
0
1
2

Appendix F3 – Details of Analyis of Variance across Differnet CSC firm charecteristics

ANOVA Between Groups – Category of CSC Firm

	Sum of Squares	df	Mean Square	F	Sig.
Qualifications	6.912	8	0.864	1.571	0.155
Staff Experience	3.769	8	0.471	0.939	0.493
Organisation's Experience	2.674	8	0.334	0.734	0.661
Administrative and Strategic Capacity	4.285	8	0.536	0.892	0.53
Technical (Physical) Resources	8.537	8	1.067	2.089	0.053
Specific BIM Modelling Capacity	4.7	8	0.588	0.771	0.629
Proposed Method of BIM Delivery	6.027	8	0.753	1.367	0.232
Reputation	12.452	8	1.556	1.135	0.355
Technology Readiness	8.537	8	1.067	2.089	0.053
Organisational Structure	18.561	8	2.32	2.186	0.043
Cost	6.786	8	0.848	1.038	0.42
BIM Modelling Success	6.531	8	0.816	1.262	0.282
CSC Success through BIM	10.508	8	1.314	1.981	0.066

ANOVA Between Groups – CSC Firm Size

	Sum of Squares	df	Mean Square	F	Sig.
Qualifications	6.316	2	3.158	6.246	0.003
Staff Experience	1.706	2	0.853	1.754	0.182
Organisation's Experience	1.581	2	0.791	1.846	0.167
Administrative and Strategic Capacity	10.033	2	5.017	11.218	0.000
Technical (Physical) Resources	9.281	2	4.641	10.349	0.000
Specific BIM Modelling Capacity	1.662	2	0.831	1.128	0.330
Proposed Method of BIM Delivery	7.803	2	3.902	8.34	0.001
Reputation	19.311	2	9.655	8.592	0.001
Technology Readiness	9.281	2	4.641	10.349	0.000
Organisational Structure	4.994	2	2.497	2.117	0.129
Cost	1.517	2	0.759	0.921	0.404
BIM Modelling Success	3.114	2	1.557	2.436	0.096
CSC Success through BIM	7.697	2	3.849	5.977	0.004

ANOVA Between Groups – CSC Firm's General Experience

	Sum of Squares	df	Mean Square	F	Sig.
Qualifications	6.432	3	2.144	4.187	0.009
Staff Experience	7.682	3	2.561	6.486	0.001
Organisation's Experience	5.986	3	1.995	5.509	0.002
Administrative and Strategic Capacity	5.821	3	1.94	3.697	0.016
Technical (Physical) Resources	13.466	3	4.489	11.624	0.000
Specific BIM Modelling Capacity	1.973	3	0.658	0.885	0.454
Proposed Method of BIM Delivery	2.294	3	0.765	1.348	0.268
Reputation	18.024	3	6.008	5.162	0.003
Technology Readiness	13.466	3	4.489	11.624	0.000
Organisational Structure	11.727	3	3.909	3.597	0.019
Cost	1.993	3	0.664	0.801	0.498
BIM Modelling Success	0.385	3	0.128	0.185	0.906
CSC Success through BIM	4.393	3	1.464	2.064	0.115

ANOVA Between Groups – CSC Firm's BIM Task Responsibility

	Sum of Squares	df	Mean Square	F	Sig.
Qualifications	11.231	3	3.744	8.443	0.000
Staff Experience	3.694	3	1.231	2.672	0.056
Organisation's Experience	4.686	3	1.562	4.235	0.009
Administrative and Strategic Capacity	5.109	3	1.703	3.157	0.031
Technical (Physical) Resources	4.367	3	1.456	3.008	0.037
Specific BIM Modelling Capacity	10.609	3	3.536	6.285	0.001
Proposed Method of BIM Delivery	8.574	3	2.858	6.137	0.001
Reputation	6.167	3	2.056	1.545	0.213
Technology Readiness	4.367	3	1.456	3.008	0.037
Organisational Structure	27.929	3	9.31	11.381	0.000
Cost	5.34	3	1.78	2.475	0.070
BIM Modelling Success	4.967	3	1.656	2.593	0.061
CSC Success through BIM	9.508	3	3.169	5.162	0.003

Appendix F4 – Main Research Varibales Correlation Matrix

		Size_Org	Gen_Exp_Org	BIMTask_Resp	IndexQual	indexExp	indexexporg	indexAdmin	indextechresource	indexBIMod	indexmeth	indexreputation	indexTechred	indexorgstruc	indexcost	IndexSucc	Index_SC_Succ
Size_Org	Pearson Correlation	1	.256*	.255*	.386**	0.116	0.239	.372**	.384**	0.143	.444**	0.242	.384**	0.222	0.158	.265*	.284*
	Sig. (2-tailed)		0.041	0.045	0.002	0.362	0.057	0.002	0.002	0.261	0	0.054	0.002	0.078	0.213	0.034	0.023
	N	64	64	62	64	64	64	64	64	64	64	64	64	64	64	64	64
Gen_Exp_Org	Pearson Correlation	.256*	1	-0.165	0.009	0.003	0.159	0.198	0.178	0.001	0.229	0.09	0.178	-0.045	0.087	0.021	-0.052
	Sig. (2-tailed)	0.041		0.2	0.945	0.982	0.21	0.116	0.158	0.994	0.068	0.48	0.158	0.727	0.492	0.866	0.686
	N	64	64	62	64	64	64	64	64	64	64	64	64	64	64	64	64
BIMTask_Resp	Pearson Correlation	.255*	-0.165	1	.384**	.329**	.418**	.364**	.278*	.438**	0.235	0.215	.278*	.527**	0.171	.258*	.443**
	Sig. (2-tailed)	0.045	0.2		0.002	0.009	0.001	0.004	0.028	0	0.066	0.094	0.028	0	0.184	0.043	0
	N	62	62	62	62	62	62	62	62	62	62	62	62	62	62	62	62
IndexQual	Pearson Correlation	.386**	0.009	.384**	1	.483**	.596**	.550**	.699**	.533**	.588**	.504**	.699**	.621**	.427**	.539**	.546**
	Sig. (2-tailed)	0.002	0.945	0.002		0	0	0	0	0	0	0	0	0	0	0	0
	N	64	64	62	64	64	64	64	64	64	64	64	64	64	64	64	64
indexExp	Pearson Correlation	0.116	0.003	.329**	.483**	1	.580**	.510**	.520**	.286*	.307*	.455**	.520**	.292*	0.097	.535**	.479**
	Sig. (2-tailed)	0.362	0.982	0.009	0		0	0	0	0.022	0.014	0	0	0.019	0.446	0	0
	N	64	64	62	64	64	64	64	64	64	64	64	64	64	64	64	64
indexexporg	Pearson Correlation	0.239	0.159	.418**	.596**	.580**	1	.521**	.628**	.611**	.448**	.298*	.628**	.500**	0.184	.447**	.538**
	Sig. (2-tailed)	0.057	0.21	0.001	0	0		0	0	0	0	0.017	0	0	0.146	0	0
	N	64	64	62	64	64	64	64	64	64	64	64	64	64	64	64	64
indexAdmin	Pearson Correlation	.372**	0.198	.364**	.550**	.510**	.521**	1	.558**	.582**	.421**	.471**	.558**	.486**	0.205	.452**	.737**
	Sig. (2-tailed)	0.002	0.116	0.004	0	0	0		0	0	0.001	0	0	0	0.104	0	0

	N	64	64	62	64	64	64	64	64	64	64	64	64	64	64	64	64
indextechresource	Pearson Correlation	.384**	0.178	.278*	.699**	.520**	.628**	.558**	1	.549**	.522**	.552**	1.000**	.526**	.379**	.381**	.505**
	Sig. (2-tailed)	0.002	0.158	0.028	0	0	0	0		0	0	0	0	0	0.002	0.002	0
	N	64	64	62	64	64	64	64	64	64	64	64	64	64	64	64	64
indexBIMod	Pearson Correlation	0.143	0.001	.438**	.533**	.286*	.611**	.582**	.549**	1	.436**	.444**	.549**	.684**	.252*	.299*	.684**
	Sig. (2-tailed)	0.261	0.994	0	0	0.022	0	0	0		0	0	0	0	0.044	0.016	0
	N	64	64	62	64	64	64	64	64	64	64	64	64	64	64	64	64
indexmeth	Pearson Correlation	.444**	0.229	0.235	.588**	.307*	.448**	.421**	.522**	.436**	1	.411**	.522**	.361**	.328**	.486**	.329**
	Sig. (2-tailed)	0	0.068	0.066	0	0.014	0	0.001	0	0		0.001	0	0.003	0.008	0	0.008
	N	64	64	62	64	64	64	64	64	64	64	64	64	64	64	64	64
indexreputation	Pearson Correlation	0.242	0.09	0.215	.504**	.455**	.298*	.471**	.552**	.444**	.411**	1	.552**	.454**	0.231	0.236	.454**
	Sig. (2-tailed)	0.054	0.48	0.094	0	0	0.017	0	0	0	0.001		0	0	0.067	0.06	0
	N	64	64	62	64	64	64	64	64	64	64	64	64	64	64	64	64
indexTechred	Pearson Correlation	.384**	0.178	.278*	.699**	.520**	.628**	.558**	1.000**	.549**	.522**	.552**	1	.526**	.379**	.381**	.505**
	Sig. (2-tailed)	0.002	0.158	0.028	0	0	0	0	0	0	0	0		0	0.002	0.002	0
	N	64	64	62	64	64	64	64	64	64	64	64	64	64	64	64	64
indexorgstruc	Pearson Correlation	0.222	-0.045	.527**	.621**	.292*	.500**	.486**	.526**	.684**	.361**	.454**	.526**	1	0.232	.437**	.620**
	Sig. (2-tailed)	0.078	0.727	0	0	0.019	0	0	0	0	0.003	0	0		0.065	0	0
	N	64	64	62	64	64	64	64	64	64	64	64	64	64	64	64	64
indexcost	Pearson Correlation	0.158	0.087	0.171	.427**	0.097	0.184	0.205	.379**	.252*	.328**	0.231	.379**	0.232	1	.415**	.280*
	Sig. (2-tailed)	0.213	0.492	0.184	0	0.446	0.146	0.104	0.002	0.044	0.008	0.067	0.002	0.065		0.001	0.025
	N	64	64	62	64	64	64	64	64	64	64	64	64	64	64	64	64
IndexSucc	Pearson Correlation	.265*	0.021	.258*	.539**	.535**	.447**	.452**	.381**	.299*	.486**	0.236	.381**	.437**	.415**	1	.601**
	Sig. (2-tailed)	0.034	0.866	0.043	0	0	0	0	0.002	0.016	0	0.06	0.002	0	0.001		0
	N	64	64	62	64	64	64	64	64	64	64	64	64	64	64	64	64

Index_SC_Succ	Pearson Correlation	.284*	-0.052	.443**	.546**	.479**	.538**	.737**	.505**	.684**	.329**	.454**	.505**	.620**	.280*	.601**	1
	Sig. (2-tailed)	0.023	0.686	0	0	0	0	0	0	0	0.008	0	0	0	0.025	0	
	N	64	64	62	64	64	64	64	64	64	64	64	64	64	64	64	64

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

Appendix F5 – Reliability Test on Main Research Varibales

Cronbach's Alpha Tests on Critical BIM Qualification Criteria

Reliability Statistics

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
.930	.932	28

Item-Total Statistics

	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Squared Multiple Correlation	Cronbach's Alpha if Item Deleted
Qual_KeyTechStaff	88.3750	262.683	.642	.	.927
Qual_BIMStaff_Avail	87.9688	263.904	.690	.	.926
Qual_OrgBIMCert	88.9219	265.978	.462	.	.929
Qual_OrgBIM_Training	87.7188	268.586	.467	.	.929
StaffExp_MgtStaff	87.7500	274.222	.283	.	.932
StaffExp_TechStaff	87.1094	270.353	.530	.	.928
OrgExp_Software	87.6563	271.213	.552	.	.928
OrgExp_PastProj	87.7188	270.967	.469	.	.929
OrgExp_SimProj	88.2969	261.006	.686	.	.926
OrgExp_CollabIT	87.9844	273.317	.364	.	.930
AdminStrat_ITVisionMission	88.1563	269.689	.478	.	.929
AdminStrat_BIMImpStra	87.7188	265.539	.714	.	.926
AdminStrat_RandD	88.0625	266.917	.506	.	.928
TechResour_Software	87.8125	263.964	.678	.	.926
TechResour_DataStor	88.4844	267.651	.596	.	.927
TechResour_Network	88.4375	264.694	.660	.	.926
BIMModCap_Standards	87.6875	254.631	.737	.	.925
BIMModCap_Naming_Clas	87.8125	262.345	.672	.	.926
BIMModCap_Maturity	88.4219	269.486	.406	.	.930
BIMModCap_LOD_LOI	87.6250	270.175	.394	.	.930
Meth_SuitBEPs	87.4688	276.570	.331	.	.930
Meth_Vendor_Inv	88.8594	263.869	.541	.	.928
Reputation	88.8594	262.916	.567	.	.928
TechRed_TR_Attitude	87.9531	256.363	.841	.	.924
TechRed_BIMBenefitsAw	87.5781	270.121	.579	.	.928
TevhRed_ITcoreProcs	88.3438	264.801	.560	.	.928
OrgStructure	88.5313	259.840	.701	.	.926
Cost	88.1250	274.365	.361	.	.930

Cronbach's Alpha Tests on Success Variables

Reliability Statistics

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
.810	.810	6

Item-Total Statistics

	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Squared Multiple Correlation	Cronbach's Alpha if Item Deleted
DSucc_Quality	19.4531	14.061	.708	.643	.747
DSucc_Shedule	19.6563	15.531	.470	.544	.803
DSucc_Budget	19.0938	15.959	.542	.397	.786
DSucc_Collab	19.8281	14.716	.605	.376	.771
DSucc_Coord	20.2813	15.602	.521	.353	.790
Dsucc_Itegrat	20.4375	14.758	.581	.555	.777

Appendix G: Authors Publications

Thesis author's publications related to research subject or cited in this thesis report

Articles

Mahamadu, A., Mahdjoubi, L. and Booth, C. (2017) Critical BIM Qualification Criteria for Construction Pre-Qualification and Selection*. Architectural Engineering and Design Management.* DOI: 10.1080/17452007.2017.1296812. Available from: http://dx.doi.org/10.1080/17452007.2017.1296812

Refereed Conferences

Mahamadu, A., Mahdjoubi, L., Booth, C. (2015) Supplier BIM Competence Assessments within the Cloud: A Proposed Fuzzy-TOPSIS Approach. In Mahdjoubi, L., Brebbia, C. A. and Laing, R. (Eds). *BIM 2015 - Building Information Modelling (BIM) in Design, Construction and Operations*. 9-11 September 2015, Bristol, UK. WIT Press.

Mahamadu, A., Mahdjoubi, L. and Booth, C. (2014) Determinants of Acceptance of Building Information Modelling (BIM) for Supplier Integration: A Conceptual Model. In Raiden A, B and Aboagye-Nimo, E (Eds). *Proceedings of 30th Annual Association of Researchers in Construction Management (ARCOM) Conference,* 1-3 September 2014, Portsmouth. pp. 723-732.

Navendren, D., Manu, P., Shelbourn, M., and **Mahamadu, A.** (2014). Challenges to building information modelling implementation in 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, UK, pp.733-742

Mahamadu, A., Mahdjoubi, L., Booth, C. (2013a) Towards Digital Information Exchange within the Construction Supply Chain. *Proceedings of Association of Researchers in Construction Management (ARCOM), Doctoral Workshop,* Birmingham City University, 20th June 2013. pp. 56-69.

Mahamadu, A., Mahdjoubi, L., Booth, C. (2013b) Challenges to BIM-cloud integration: Implication of security issues on secure collaboration. *Proceedings of IEEE 5th International Conference on Cloud Computing Technology and Science (CloudCom) - Cloud-BIM Services for the Built Environment*. 2-5, December, 2015, Bristol, UK.

Mahamadu, A., Mahdjoubi, L., Booth, C. (2013c) Challenges to Digital Collaborative Exchange for Sustainable Project Delivery through Building Information Modelling Technologies. In S.S Zubir and C.A Brebbia, (Eds). *Proccedings of 8th International Conference on Urban Regeneration and Sustainability,* Wessex Institute of Technology. 3 - 5 December, 2013, Putrajaya, Malaysia. Pp. 547 to 557.

Thesis author’s publication not related to study but developed during research period as a result of research training

Article or Book Chapter

Mahamadu, A., Baffour-Awuah, K. and Booth, C. (2016) Principles of sustainability and life-cycle-analysis in J. Khatib (Ed). Sustainability of Construction Materials. 2nd Ed, Elsevier **(Under Review).**

Mahamadu, A., L. Mahdjoubi, L., Booth, C. and Fewings, P (2015) Integrated Delivery of Quality, Safety and Environment through Road Sector Procurement: the case of Public Sector Agencies in Ghana. Journal of Construction in Developing Countries. 20(1) pp.1-24

Navendren, D., Manu, P., **Mahamadu, A**. and Shelbourn, M. (2014) Towards exploring profession-specific BIM challenges in the UK. Briefing- ICE - Management, Procurement and Law, 167(4), pp. 163-166.

Refereed Conferences

Nguyen, T.T., Manu, P. **Mahamadu**, **A**. and Ash, S (2015) Inquiry into the Health and Safety Management Practices of Contractors in Vietnam: Preliminary Findings. In Proceedings of CIB W099-Benefitting Workers and Society through Inherently Safe(r) Construction. Belfast, Northern Ireland, 10-11 September 2015

Addo Duah, P., Westcott, T., Booth, B, Mason, J and **Mahamadu, A.** (2014) Developing capability of public sector procurement in Ghana: An assessment of the road subsector client. In Castro-Lacouture, D et al (Eds) Proceedings of Construction Research Congress (CRC) 2014. Atlanta, GA, USA May 19-21, 2014. Pp. 2053-2062