School of Design and the Built Environment

A Hybrid OSM–BIM Framework for Construction Management System

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Declaration

To the best of my knowledge and belief, this thesis contains no material previously published by any other person except where due acknowledgement has been made. This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

The research presented and reported in this thesis was conducted in accordance with the National Health and Medical Research Council National Statement on Ethical Conduct in Human Research (2007) – updated March 2014. The proposed research study received human research ethics approval from the Curtin University Human Research Ethics Committee (EC00262), Approval Number #HRE2019-0070.

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Abstract

Building information modelling (BIM) and off-site manufacturing (OSM) are advanced techniques, which emerged to promote project performance through the improvement of key productivity indicators (KPrIs). In theory, BIM and OSM optimise performance aspects, including time, cost, quality, safety and stockholders' satisfaction. However, reports have not yet confirmed that BIM and OSM have fulfilled the objectives set out for their overall project performance. The overall project performance is subject to the improvement of construction productivity. These techniques may require the help of some more productivity fundamentals, in addition to their own capabilities. Therefore, this research developed the interactions between OSM and BIM and determined the influence of OSM–BIM interactions to maximize overall project performance. Extensive literature review and relevant analysis techniques were adopted to obtain a comprehensive understanding for the development of a hybrid OSM–BIM system. This research had four objectives. The first objective required an all-embracing review of poor productivity roots in construction projects, to identify a range of productivity fundamentals that support the capabilities of the most common and advanced techniques. Then the research was narrowed in scope to focus on BIM application in OSM-based projects. The second objective was to formulate an insightful, interactive picture of the influential standalone capabilities of each technique, for a hybrid, OSM–BIM conceptual framework contributing to the project performance. The third objective was to identify KPrIs and investigate the capabilities of OSM and BIM techniques in detail—as well as their potential interactions for productivity improvement. The fourth objective was to determine the influences of OSM–BIM interactions on overall project performance, using an in-depth, complex evaluation of the practicality of the interactions. Structural equation modelling (SEM) was adopted to examine the complex relationships among variables in data acquired via a questionnaire survey. Twelve OSM–BIM interactions were developed and evaluated from the perspective of productivity improvement. The findings showed that BIM and OSM had no significant influence on overall project performance in Australia when applied individually. However, BIM had a significant influence on OSM, meaning that the capabilities of the two techniques were interactive. Further, OSM–BIM interactions had a significant influence on overall project performance. From a theoretical perspective, the technical details that delivered these interactions provide new insights into removing inefficiencies in OSM-based projects via BIM application. The outcome of this research is aligned with the diffusion of innovation theory in the construction industry because it has clarified three essential elements of innovation: idea generation, opportunities, and diffusion.

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List of Publications Included as Part of the Thesis

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Sabet, P. & Chong, H. Y (2019). Interactions between building information modelling and off-site manufacturing for productivity improvement. International Journal of Managing Projects in Business, Vol. 13 No. 2, pp. 233-255. https://doi.org/10.1108/IJMPB-08-2018-0168

Sabet, P., & Chong, H.Y. (2018). A conceptual hybrid OSM-BIM framework to improve construction project performance. Educating Building Professionals for the Future in the Globalised World, Singapore, pp. 204-213, September 26-28.

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Statement of Author's Contributions

Co-author statements declaring and endorsing the candidate's contributions to each paper included in this thesis can be found in Appendix F-J.

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Glossary of Terms

BIM	Building Information Modelling
CAD	Computer Aided Drafting
KPrIs	Key Productivity Indicators
SEM	Structural Equation Modelling
OSM	Off-Site Manufacturing
POBIs	Potential OSM–BIM Interactions
TQM	Total Quality Management
UK	United Kingdom
US	United States
WBS	Work Breakdown Structure
3D	3 modelling/Dimensional
CA	Constructability assessment
ME	Measurement/estimation
CD	Clash detection
SC	Sequence clarification
SMB	Safety management
PS	Planning and scheduling
SC	Site coordination
AP	Automation and series production
SM	Safety management
ISLM	Interaction of Sequence and location management
IPS	Interaction of Planning and scheduling
ISM	Interaction of Safety management
IST	Interaction of sustainability
IIM	Interaction of Interface management
ICC	Interaction of Contract condition
IIT	Interaction of Information technology

IVE	Interaction of Value engineering
ICE	Interaction of Concurrent engineering
Qt	Quality
Ct	Cost
Tm	Time
Sf	Safety

Chapter 1: Introduction

1.1 Introduction

This chapter details the development of the thesis structure. As the beginning of this chapter, it elaborates on the research background and the aim of the research. This is followed by an exegesis of the thesis structure, which discusses the five underpinning objectives of the research. Research methodologies used in this research are also explained in this chapter.

1.2 Research Background and Aim of the research

Business competition and demands, cultural changes and constant environmental changes have made the construction industry one of the most complicated industries currently. Growth in the construction industry means that the selection of the conventional design–build method does not sufficiently respond to high demands of project performance anymore (Xia et al., 2013). Gross domestic product (GDP) is one of the most significant indicators in determining the economic status of a country. China, as one of the industry leaders, has been benefiting from considerable savings on GDP from the modernisation of its construction industry. Considerations for increasing productivity through manufacturing have contributed to GDP improvement in Malaysia as well as Australia (Ibrahim et al., 2010; Khalfan & Maqsood, 2014). Even a small productivity improvement in the construction industry can be remarkable and can significantly contribute to national GDP improvements in Australia, as well (Khalfan & Maqsood, 2014). Addressing inefficiencies and ineffectiveness in executing construction projects have always been on top of the agenda. Many new techniques based on different management approaches have been developed to reduce and eliminate inefficiencies and ineffectiveness. The stakeholders in the Malaysian construction industry have realised that there is a need to unify a project, throughout its lifecycle, to avoid the issue of fragmentation in industrialised buildings (Mohammad, Shukor, Mahbub, & Halil, 2014; Nawi, Lee, Azman, & Kamar, 2014). The core of the issue has been labelled 'communication-conflict interaction' (Wu et al., 2017 p. 1466). That is, the parties involved in a project need to be linked to each other to minimise the chances of any potential conflict, and the huge amount of information generated needs to be shared among the parties. Computer-based information systems are among the new arrivals in the construction industry that have attracted attention in this regard.

Construction decision-makers, including clients and consultants, expect construction contractors (as a sub-organisation partnering in a project) to adopt measures such as appropriate management methods, professional workforces and modern technologies to satisfy the productive supply chain (Beach et al., 2005).

As a new technique, BIM still raises doubts, questions, reluctance and misunderstandings among construction professionals about its potential benefits and the correct, consistent and influential level of BIM use to push projects forward through the current challenges in the industry (Barlish & Sullivan, 2012). Estimator professionals believe that BIM can optimise the estimation process dramatically, but there are some barriers; for example, the full and accurate model for the quantity surveyors needs to be accessible (McCuen, 2015; Smith, 2016).

1.2.1 The need for productivity improvement.

Construction improvement has attracted the attention of governments in such a way that huge research funds are assigned to achieve it, as a priority. The UK government has asked contractors to improve their productivity, as the main leverage for success, via advanced managerial strategies and tools, consistent with the competitive market. Offering projects with reasonable quality at the fastest pace of progress, and with lower costs, is directly linked to companies' survivability and profitability in the competitive market. Productivity is an influential factor, which determines whether a company will be selected to perform a project (Thomas & Sudhakumar, 2012). As far as the response to the demand for productivity is concerned, companies could either benefit or lose (Mahamid, 2013).

Low productivity is caused by ineffective strategies in running a project. This issue results in loss of control of the construction process. The project, under these circumstances, would face delay so that the interests linked to the project would be lost. Productivity growth equals time and cost optimisation which benefit stockholders, and, in many countries, low-productivity projects have been criticised in the construction industry (Kagioglou et al., 2001).

Productivity growth is a managerial scheme. Therefore, an appropriate strategy to embrace new techniques could accelerate that growth. Different themes, such as cultural, educational, technical and organisational could remove the barriers to improvement (Rojas & Aramvareekul, 2003).

Rethinking construction concepts has brought about new ideas to limit inefficiencies in the industry. For instance, it is believed that new managerial styles, such as ‘lean’ could create efficient resource availability (Thomas, Horman, Minchin, & Chen, 2003) via site management skills, appropriate planning, effective administration and implementation and continuous project control within the whole life cycle (Aziz & Hafez, 2013). Without the correct recognition of productivity indicators, productivity growth would not be possible. The potential of productivity growth could be achieved through five areas: information technology, project delivery, automation and prefabrication, workforce development, and materials suitability (Enshassi, Kochendoerfer, & Abed, 2013).

It has been observed, through the literature review, that the factors affecting construction productivity can be categorised under a wide range of indicators, such as company's characteristics, labour, material, management, regulation, machinery, contract conditions, information technology, engineering, labour improvement and external circumstances (Takim & Akintoye, 2002; Cox, Issa, & Ahrens, 2003; Bassioni, Price, & Hassan, 2004; Chan, 2009; Chan, Scott, & Chan, 2004; Meng, 2012; Kapelko, Horta, Camanho, & Lansink, 2015; Poirier, Staub-French, & Forgues, 2015). These indicators can be categorised as the key productivity indicators (KPrIs).

The number of factors contributing to productivity growth differs between different sectors. Arditi and Mochtar (2000) state that 'the functions that were identified as needing more improvement were new materials, value engineering, prefabrication, labor availability, labor training, quality control'~~(p.150).~~ OSM sectors constantly achieved better productivity improvement among the improvable factors (Eastman & Sacks, 2008).

1.2.2 Value-making approaches (VmAs).

Efforts via VmAs approaches focus on the elimination of inefficiencies and ineffectiveness. These approaches recommend applying systematic innovative methods to remove unnecessary costs, promoting quality and performance through teamwork and unifying activities for value improvement (Smith & Colgate, 2007).

1.2.3 Total quality management and Deming cycle.

Management style, as one of the tools in managers' hands, can help to achieve reasonable productivity levels (Male et al., 2007). To successfully conduct a project, proper management styles and techniques must be widely discussed, regarding planning and time, cost and quality control (Munns & Bjeirmi, 1996). A managerial approach clarifying constructive concepts and tasks can contribute significantly to achieving the goals in a project. Therefore, a proper management style welcoming any action to improve productivity can also contribute significantly to the perfect completion of construction projects (Walker, 2015).

Quality management systems originated from the concept of total quality management (TQM). The achievement of the objectives of these systems is subject to a well-organised, functioning system and integrated stakeholders (Klufallah, Hasmori, Said, & Idris, 2010). Continuous improvement is one of the principles in TQM, which is achievable in the Deming cycle. As clients' satisfaction is followed by continuous improvement, it can be claimed that the Deming cycle is the core of the TQM concept. The Deming cycle has been defined and explained in different sources, such as PM book and ISO standards. It involves four procedures: planning, doing, checking and acting. Generally, quality comes from this concept (Sokovic et al., 2010). Development of value-making approaches (VmAs) in the construction industry has been on the agenda at governmental forums. As pointed out, total quality management method targeted to create value via the improvement of quality. Every consideration contributing to the optimisation of the dimensions of project performance, which include time, cost, quality, safety and stakeholders' satisfaction, refers to values. The application of advanced techniques, such as OSM and BIM, has been considered to create value.

1.2.4 Statement of the problem and research gap

Among the new techniques, BIM, as an IT-based technique, has been introduced to complement off-site manufacturing (OSM). There are positive point of views among the professional to maximise the capabilities of these techniques by paring up BIM and OSM, but there has not been a systematic direction of adopting them concurrently. In recent years, advanced techniques, such as prefabrication, automation and IT-based techniques, have drastically altered the construction industry, changing its focus from traditional practice to modern enterprise (Nam et al., 2019). Building information modelling (BIM) is recommended as an effective tool to meet project success criteria. Its application leads to ‘improving actions towards technology transfer into productivity’ (Zhang et al., 2015). Zhang et al. (2015) believed that BIM, as a new technique, has potential to become the predominant technique used in the construction industry for productivity improvement. Goodier and Gibbs (2007) claimed that OSM-based projects observe a perfect project completion. They described OSM as a technique to improve productivity in which off-site components and on-site structures are combined in an optimum period. Although there have been issues on OSM-based projects, Industry professionals and academics from countries such as Australia, the UK, Malaysia, Hong Kong and Singapore have argued that the advantages of OSM outweigh its disadvantages (Blismas, 2007). Therefore, further efforts are needed to prove that OSM and BIM can be used to optimise construction projects in terms of time, cost and quality performance.

Based on the literature available, attempts to combine OSM and BIM to improve productivity are still in their infancy. It seems that there are still conflicting ideas among decision-makers in this regard, either owing to overlooking details or negligence in their evaluation (Hosseini et al., 2018).

1.2.5 The idea of BIM in OSM

New techniques and materials have changed the construction industry in recent decades. Some highlighted new techniques include GIS, Big data, Virtual reality, Augment reality, BIM, OSM, etc. have attracted the industry's stakeholders. As different countries have their policies to adopt these new techniques, some reports inform a lack of objectives fulfillment expected via some techniques. To solve this problem, some researchers have recommended combining some of the techniques. They provide the client and the stakeholders with some evidence on the capabilities of these interactions. Among those techniques, BIM in OSM and BIM in Lean construction have been identified to improve the construction industry. This research study focuses on fostering the idea of BIM in OSM.

The current research aims to pair up OSM and BIM functions and practices for a systematic adoption to maximise benefits. Seemingly, BIM specifications are very capable of being integrated into the Deming cycle concept in OSM-based projects. Figure 1.1 indicates that there should be some inbounding points, so that the capabilities, function and practices of the two techniques are injectable into the cycle, to optimise the product. This reflects a unique systematic adoption of BIM in OSM-based projects.

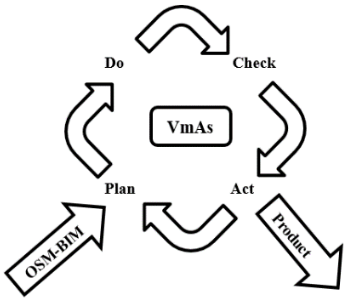

Figure 1.1. OSM–BIM in Deming cycle.

Based on the explanations above, the following question needs to be addressed: ‘How can BIM be properly applied in the OSM-based projects to fulfil the objectives of both techniques in the productivity improvements followed by project performance?’ Therefore, this research aims to:

Determine the influences of OSM–BIM interactions on project productivity that result in project performance.

1.3 Exegesis of Thesis Structure

An extensive, in-depth review of the role of OSM and BIM as advanced techniques in construction productivity, followed by a data analysis, allows for a better understanding of this research.

First, this chapter explains how the subset objectives address the aim of the research. A micro-to-macro method was used to assemble the relevant literature. Each dimension of this two-dimensional view interacts with the other, for a more efficient analysis of the application of the advanced techniques (Wagner & Derryberry, 1998). The micro-dimension examines the discovery of individuals and their interactions that may contribute to a framework. The macro dimension examines the impact of the discovered individual contributor and any potential interactions in a functioning system. The outcomes achieved through the micro-level method are the prerequisite of any actions at the macro-level method (Billari, 2015). In this research, the micro dimension examines the range of productivity fundamentals and identifies the KPrIs. This results in a supplementary foundation, on which advanced techniques, specifically OSM and BIM, should be applied. The macro dimension determines the practicality of using OSM and BIM throughout the project stages that can improve the KPrIs.

Therefore, the objectives have been developed as follows:

1.3.1 Pathways for the improvement of construction productivity: A perspective on the adoption of advanced techniques.

The first objective of this thesis is formulated as follows:

Objective 1: to identify productivity fundamentals and highlight the role of advanced techniques for productivity improvement.

The construction industry plays a significant role in the economy of any countries. Fragmentation issues, improper choice of techniques and inappropriate management result in inefficiencies such as cost and time overrun, which fall under the theme of poor productivity (Bresnen, & Marshall, 2000; & Ganesan, 1984). This issue has always challenged both the stockholders’ presence in the competitive market and clients’ profitability. Fundamental changes have been suggested to improve productivity (Force, 1998). Researchers and practitioners have been invited to develop new strategies to overcome these challenges. The theorisation of the new strategies and techniques, followed by their successful establishment, requires a strong leadership, recognition of customers’ needs, influential collaboration and a proper project process. The innovation of advanced techniques and integrating systems are subject to the recognition of weak points and the perpetration of a range of fundamental supports in the current circumstances (Changali et al., 2015; Winch, 1998). A quick decision-making process is inseparable leverage for a successful, functioning system (Changali et al., 2015). Undoubtedly, the lack of contract clarification can appear as a disturbing agent, even though a properly functioning system is in place and an appropriate advanced technique is implemented. The advanced techniques are to deal with project performance via key productivity indicators. Cost benefit analysis and return on investment (ROI) have been used to evaluate project performance from the implementation of the new techniques and technologies. However, those techniques can not cover all areas of KPrIs and need to be reinforced by a range of fundamentals contributing to the final productivity. This argument provides practitioners with a holistic understanding of the root of poor project productivity and the pathways through which the new, advanced techniques can affect different aspects of performance. The range of productivity fundamentals can act as catalysts or reinforcers that contribute to the improvement of the functioning system in the implementation of the advanced techniques.

Chapter 3 of this thesis has been published as an article, which fulfilled this aim. A wide, scoping review of 128 academic publications contributing to productivity fundamentals and advanced techniques was made. This study discovered a range of productivity fundamentals (Table 3.1), which were applicable where the capabilities of the new advanced techniques could not cover all areas of KPrIs and the integration of these fundamentals is required. Figure 3.2 conceptualised a generic pathway that linked the productivity fundamentals and the advanced techniques to the final project performance.

1.3.2 The current influential standalone capabilities of BIM and OSM for a hybrid OSM–BIM conceptual framework.

The second objective has been developed according to the following explanations.

Objective 2: To review the current influential standalone capabilities of BIM and OSM for a hybrid OSM–BIM conceptual framework.

The development of influential, advanced techniques, underpinned by technology evolution, have been noted as a solution to construction productivity. Every technique, with its own specific objectives and capabilities, aims to upgrade the construction industry. However, the fulfilment of some objectives has faced challenges in practice and the outcome has been far behind what was theorised. These techniques are not able to cover all areas of productivity improvement. Some researchers have found it useful to combine IT-based advanced techniques (Zhu & Augenbroe, 2006) with the other newly advanced techniques. They believe that the concurrent application of the techniques can cover one another and can enhance the projects' output (Segerstedt & Olofsson, 2010). They argued that the weak points of one technique could be overlapped by the strength of the other technique. Therefore, the level of productivity improvement could be better enhanced. Some construction practitioners have criticised OSM for the inefficiencies reported from OSM-based projects. They found that the fragmentation among the parties and lack of clarification regarding the specifications of manufactured components disturb the assembly process and eventually distract from the productivity trend. BIM, as an IT-based technique, has been noted as a potential support for OSM to overcome these challenges, but this evolution takes time and effort—from idea formulation to the establishment of an OSM–BIM hybrid technique. The first step to this end is to conceptualise how to pair up these two techniques.

A publication, recorded in Chapter 4, shows how to achieve the second objective. Figure 4.5 is the hybrid conceptual framework for the overall project performance, drawn after the deep review of 47 academic publications, to gain the required understanding to formulate the idea of BIM in OSM.

1.3.3 The identification of potential interactions between BIM and OSM for productivity improvement.

The third objective is formulated as follows:

Objective 3: to identify potential interactions of BIM and OSM for productivity improvement.

‘Productivity rate’ refers to the coefficient obtained from dividing the input (what is required to progress the construction) by the output (the value of the construction progress). Productivity is aligned with project performance. This means that the productivity indicators deal with performance criteria. Therefore, identifying the KPrIs and improving them can guarantee the project performance. Low construction productivity has been flagged for decades and authorities have asked for solutions to overcome this crisis. The development and application of new, advanced techniques has been advised by researchers to upgrade construction methods (Blayse & Manley, 2004).

Some newly emerged techniques could not satisfy the productivity expectations—contrary to what had been claimed in theory. BIM and OSM are the new revolutionary techniques, but there are still arguments that they have not fulfilled their objectives for productivity improvement. A limited number of researchers believe that OSM-based projects can be supported by BIM (Goulding, Pour Rahimian, Arif, & Sharp, 2012). However, a systematic adoption of OSM–BIM-based projects has not been addressed yet. In this regard, a conceptual framework of KPrIs is needed. Following that, the standalone capabilities of the two techniques need to be scanned, to inform how they should be paired up for a range of practical interactions to improve KPrIs.

Chapter 5 is a publication discussing the achievement of the third objective. It involved critically reviewing 100 academic publications to support the objective. Figure 5.1 shows a demographic framework of KPrIs. The methodology pathways are shown in Figure 5.3. Table 5.2 and 5.3 show the nominated KPrIs that can be improved by the two techniques individually, while Table 5.4 shows the indicators affected by OSM–BIM interactions. Overall, 12 potential interactions were identified between OSM and BIM to improve KPrIs. Figure 5.4 conceptualises how the capabilities of OSM and BIM can affect project performance at the pre-construction and construction stages.

1.3.4 The influences of interactions between BIM and OSM on project performance via productivity improvement.

The fourth objective has been developed as follows.

Objective 4: to determine the influences of the standalone capabilities of OSM and BIM, as well as their interactions, on project performance.

Irresponsive productivity levels in the construction industry have led authorities to encourage fundamental changes in construction methods. Numerus studies have been carried out to upgrade the industry, but the industry is still struggling to satisfy the clients and the stockholders' expectations of productivity (Barbosa et al., 2017). Although advanced techniques have considerably affected the industry, productivity is still lagging below a satisfactory level (Sabet & Chong, 2018). The systematic adoption of BIM provides other techniques with overlapping capabilities that might maximise their functionality. For example, BIM, as a technique, and providing a collaborative environment, can pair up with lean (Sacks, Koskela, Dave, & Owen, 2010). Nawari (2012) and Wynn et al. (2013) believe that BIM, with its IT-based nature, enhances efficiency in OSM. Potential interactions between BIM and OSM have been found to be capable of improving KPrIs to meet project performance criteria. These interactions are capable of being applied in the planning and managerial stages (Sabet & Chong, 2019). Sabet and Chong (2019) have hypothesised relationships among three units, namely, BIM capabilities, OSM capabilities, OSM–BIM interactions and project performance, to evaluate the practicality of the interactions.

The capabilities and the interactions were put in the judgement of construction practitioners to determine their relationships with the project performance.

The pathway of how to achieve the fourth objective is discussed in Chapter 6. Based on this discussion, a publication is under review. The hypothetical model was tested via SEM, using AMOS software. Figure 5.3 reveals the degree of influence of each capability and their interactions. This figure also shows the direct and indirect influences of OSM, BIM and a hybrid OSM–BIM techniques on project performance (via KPrIs), once they are applied individually and concurrently.

1.4 Summary

This chapter has highlighted a gap in productivity fundamentals, which are required to reinforce the implementation of new advanced techniques for productivity improvement. It was argued that the capabilities of the advanced techniques could not cover all the areas of productivity indicators. Then, the research focused on a systematic adoption of BIM in OSM-based projects, among the other advanced techniques. The systematic adoption was referred to an effective and efficient application of BIM, to eliminate inefficiencies in time, cost, quality, safety and stockholders’ satisfaction in OSM-based projects. In addition, the measures to pair up the capabilities of these two techniques were referred to as the development of OSM–BIM interactions. These interactions affect KPrIs, which supports project performance. The research methodology was also discussed in this chapter.

Chapter 2: Research Methodology

A description of research methodology details the type of data that the study required, the sampling method, the manner in which potential respondents were approached and the data collection and analysis techniques (Easterday, Rees Lewis, & Gerber, 2018; Choy, 2014). In this research, a quantitative research methodology was established to achieve the aim of the study through an inductive approach. This chapter clarifies the research strategy and applicable terms.

2.1 Research

Research involves conducting observation, analysis, survey, experiments, study, reasoning, comparison and other activities to accurately achieve results in a standardised and organised fashion, based on verifiable facts, which may solve issues in societies or scientific fields (Towne & Shavelson, 2002). Shuttleworth (2008) specified that research is a systematic procedure to find new information. This study provides a framework for systematically adopting a concurrent application of OSM and BIM techniques. This type of research can play a great role in expanding and improving certain fields such as the development of theories and diffusion of innovation. Bunge (2012) stated that, based on research findings, researchers can anticipate future events, establish and promote ideas, and form conjectures about the relationships between variables. Therefore, research can have the function of developing theories formed or suggested in previous studies.

2.2 Inductive Approach

The term inductive approach, or inductive reasoning, refers to the approach of developing a theory based on pieces of evidence. Observations are made at the beginning of the research and the theory is developed in almost the final stage (Sabherwal & King, 1991). This type of research aims to discover a pattern by extending existing evidence by developing and evaluating hypotheses during the study. Research with an inductive approach is not initiated based on any theory, and hence, the researcher can change course and test hypotheses with a view to moving towards meaningful answers to the research questions (Thomas, 2006). The basis of this approach is learning from existing knowledge and experience, that is, drawing conclusions or building theories (Jebreen, 2012).

The aim of this research was informed by existing evidence pertaining to the combined use of BIM and OSM as advanced techniques. Subsequent data collection and analysis revealed more evidence, which developed the domain of interactions between OSM and BIM and provided a basis for examining their potential for use in productivity improvement.

2.3 Research Methodology

2.3.1 Quantitative methodology.

A quantitative research method aims to answer questions about potential relationships and the degrees of effects among variables. The inputs in quantitative research comprise numerical and standardised data (Martin & Bridgmon, 2012). Martin and Bridgmon (2012) explained that interpreting results obtained through this method is uncomplicated because they are numerical values, which are obtained by assessing participants’ performance, behaviours and opinions. The data collected in this type of research can be extended to larger populations. Moreover, the data can be efficiently explained in the form of quantitative graphs and charts.

Munn, Porritt, Lockwood, Aromataris and Pearson (2014) claimed that quantitative research is based on confidence and certainty because it has the features of empirical studies, in which practical symbols are used for every phenomenon and truth is signified. This means that researchers can explore every incident and avoid being affected by, or affecting, that incident. Analysing and interpreting the findings in this type of research is quantifiable because it directly relies on its original plans.

2.4 The research methodology of this study

This hybrid thesis contains four academic publications (three published and one under review) to meet the research objectives in chapters 3, 4, 5 and 6. The research methodology for each objective is comprehensively discussed in the relevant chapters. The following sub-sections provide a brief overview.

2.4.1 The research methodology to meet the first and the second objectives.

The implementation of advanced techniques has previously been identified as a potential solution to a lack of project productivity. However, the expected level of the productivity that lies in project performance has remained a challenge. The first objective was to identify productivity fundamentals and highlight the role of advanced techniques for productivity improvement. As the objective implies, productivity fundamentals and advanced techniques were the two units examined. To this end, a micro-to-macro level search was required to satisfy the objective. A comprehensive scoping review was applied (a) to identify the root of poor productivity, upon which a range of productive fundamentals was to be developed; (b) to identify the stages at which these fundamentals must be applied; and (c) to highlight the pathways through which the common advanced techniques improved project performance. The scoping review was also tasked with identifying potential gaps that caused performance level to be lower than expected even after applying advanced techniques'. The second objective of this research was to investigate the current, influential standalone capabilities of BIM and OSM for a hybrid OSM–BIM conceptual framework. An extensive and in-depth scoping review was required to clarify each technique's capabilities and construct an OSM–BIM hybrid foundation. Literature surrounding BIM and OSM was collected.

Papers that clarified project performance were also selected. The papers were filtered based on their abstracts to ascertain whether the papers had information that would clarify the capabilities of the two techniques. An analytical and critical perspective was applied to scan the papers. Subsequently, the idea of combining OSM and BIM for systematic adoption was fostered and formulated.

A literature review surrounding resources, management, engineering and innovation was necessary to substantiate the appropriateness of the units of construct in this research. Literature in these areas was collected, filtered and scanned, then assembled into a collection of relevant materials. Figure 3.1 shows the methodology to achieve the first objective.

2.4.2 The research methodology to meet the third objective.

Existing literature that suggests applying BIM in OSM does not describe a systematic adoption framework for pairing the capabilities of the two techniques. However, every constructive interaction is subject to systematic adoption. The capabilities could potentially overlap regarding project productivity. Identifying the KPrIs was necessary to discover the pathway through which potential interactions could improve them. Therefore, the third objective was to identify potential interactions between BIM and OSM for productivity improvement. The literature review comprised a scoping review and systematic review. The scoping review was used to gain a holistic understanding of the elements of the study, while the systematic review summarised all relevant papers regarding BIM in OSM. The process started with the scoping review. Six categories were identified as indicators in construction productivity (either individually or synergistically), namely resources, management, engineering, procurement and contracts, information technology and sustainability. The second stage involved searching the channels of evidence, including the collection and filtration by type of literature. Relevant papers were identified by keyword searches in Google Scholar and library databases, and their relevance was assessed by examining their abstracts. Figure 5.3 shows the selection process for the literature review. The question of how the potential OSM–BIM interactions could improve construction productivity was pursued.

2.4.3 The research methodology to meet the fourth objective.

Determining factors for selecting a suitable research methodology include limitations such as budget and time shortages, research potential, and the willingness of (human) subjects (Brannen, 2005). The research methodology must ensure that data will be unvarying and consistent (reliability), and that the unessential and unrelated variables are excluded so that the final instrument can measure the targeted variables accurately (validity) (Golafshani, 2003). As pointed out earlier in this section, this research aimed to measure the individual capabilities of BIM and OSM techniques, the practicality of interactions between them. Therefore, in the first round of the pilot study, the authors approached several leaders in the industry and academia to determine how to effectively convince the respondents to participate in the study. A quantitative method was advised, based on the potential desires of respondents within the study scope.

Martin and Bridgmon (2012) explained that interpreting results obtained through this method is uncomplicated. The results are numerical values, which are obtained by assessing participants’ performance, behaviours and opinions. Munn et al. (2014) claimed that quantitative research is based on confidence and certainty because it has the features of empirical studies, in which practical symbols are used for every phenomenon and truth is signified.

After the first round of pilot study, the authors applied two more rounds of pilot studies. In the second round, for construct validity, the authors double-checked the measurement constructs with the leaders from the first round. In the third round, observable variables were discussed with several experts and seniors who had a holistic understanding of both approaches. In other words, for content validity, the authors developed the statements indicating the potential applicability of the capabilities and interactions. At this stage, the authors ensured that the statements were in a digestible format and able to accurately measure the targets. After data collection stage, the hypothetical model was evaluated using SEM, through Amos software. Cronbach’s alpha was used to evaluate the data reliability. In addition, regression tests were applied to identify the existence of any relationships and reveal the variables’ degrees of influence in the hypothetical model.

Figure 6.2 depicts the stages of this part of research. The first stage involved a literature review of BIM, OSM and BIM in OSM, followed by the identification of gaps in research. In Chapter six, six hypotheses were developed to evaluate the relationships between latent and observable variables. Table 6.1 displays the constructs and the observable variables by which the latent variables could be measured. Observable variables were discussed with several experts and seniors in the industry and academia who had a holistic understanding of the two approaches. Their wealth of experience in academia and the industry facilitated the identification of observable variables, which were then used to develop a questionnaire as the data collection tool for this study.

Australia was selected as the location of this research study. Construction practitioners with relevant expertise were provided with a Qualtrics survey link. Paper questionnaires were also distributed. Engineers Australia significantly supported this research. The research was officially introduced to their members, who were encouraged to participate in the survey. Subsequently, the research team approached those practitioners through LinkedIn and advised them about the research. LinkedIn was observed to be the best platform to learn about the background of potential participants.

Practitioners' profiles allowed the research team to target those who were knowledgeable about, or experienced in, OSM and BIM. Additionally, the research team met with several seniors in academia and representatives of construction companies, in person and virtually. Prior to conducting the survey, the comprehensibility and validity of the observable variables was tested in the pilot study with ten randomly selected construction practitioners. The hypothetical test results determined whether the hypothetical model was successful or needed revision. The result showed that two out of six hypotheses were not supported.

2.5 Summary

A wide literature review, including the scoping and systematic reviews, was conducted to scan the productivity fundamentals and indicators and the capabilities of the advanced techniques, with a focus on OSM and BIM, to identify any potential interactions between them followed by an empirical study to evaluate the hypothetical model of relationships between the two selected techniques.

A quantitative research methodology was used to achieve the aim of the research. To evaluate the validity of the hypothetical model, an online survey on the application of the two techniques among construction practitioners was performed. The collection of data involved 687 construction practitioners in different regions of Australia. They were involved in the planning, design, construction, engineering, contract and procurement. They were approached via LinkedIn, e-mail and face-to-face meeting. The questionnaire included questions related to their understanding of the two techniques, obtained via academic studies and professional experience.

To investigate the relationship between the research units, a Likert scale ranging from one to five (such as, from 'strongly agree' to 'strongly disagree') was used. A two-round pilot survey was conducted to revise the questions. The data from the valid questionnaires were analysed via structural equation modelling (SEM) using AMOS software. This method was selected because of the capacity of SEM-based method to deal with complex models (Rigdon et al., 2017). The research procedures have been consolidated and explained in a flowchart approach to make clear the overall research methodology, are shown in Figure 2.2.

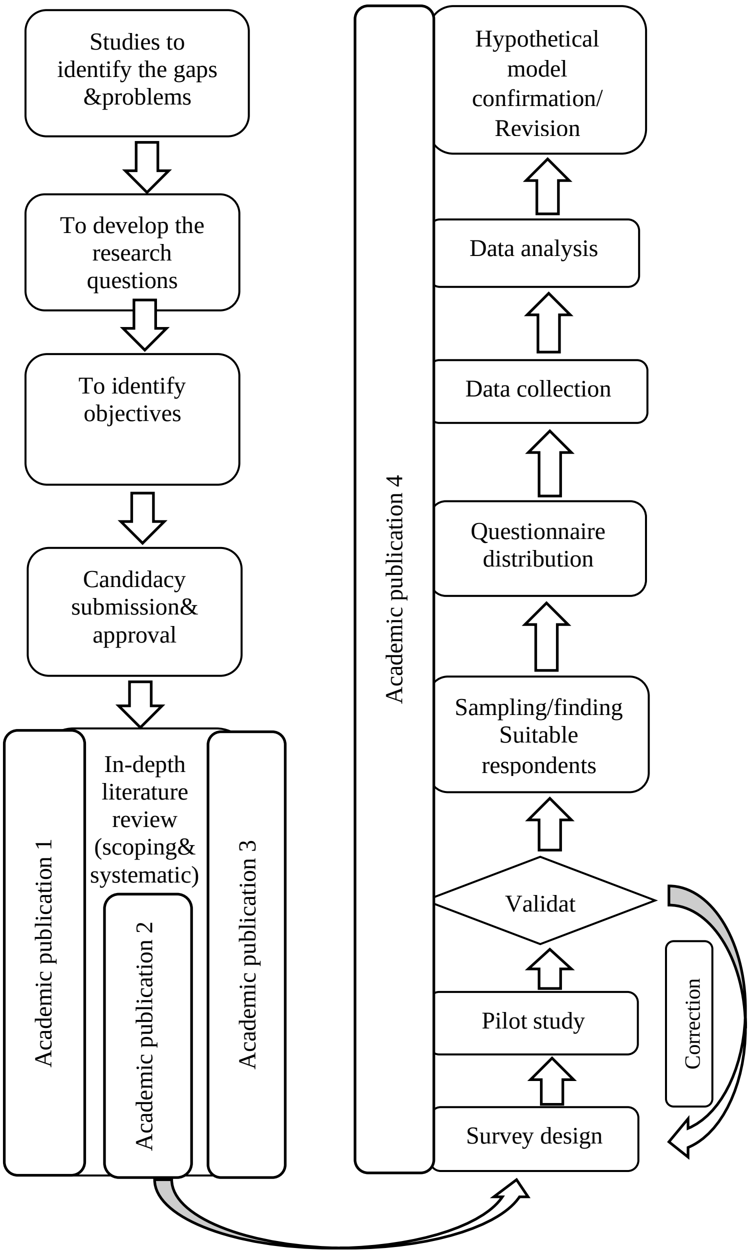

Figure 2.2. Research procedures.

Chapter 3: Pathways for the Improvement of Construction Productivity: A Perspective on the Adoption of Advanced Techniques

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Abstract

Reinventing construction is the key to improving productivity. This reinvention refers to not only inventing advanced materials and equipment, but also to developing new operating systems for construction projects. Inadequate application of advanced techniques impedes the operating system. Further, the capabilities of advanced techniques may not cover all areas required to meet the expected productivity level. The implications of these advanced techniques need to be reinforced by a range of productive fundamentals that remain unclarified. Further, the pathways through which these fundamentals can be aligned with the implementation of advanced techniques remain under-researched. Hence, the objectives of this research are: (1) to clarify how the selected and common advanced techniques applied in this paper influence construction productivity; (2) to determine the range of productivity fundamentals required to reinforce the implementation of the advanced techniques necessary to fulfil productivity expectations; and (3) to conceptualise the integration of these productivity fundamentals with the application of advanced techniques. A scoping review of 128 articles was used to identify which fundamentals can contribute to achieving performance targets once practising these new advanced techniques. The findings reveal a comprehensive range of productivity fundamentals that are able to reinforce new advanced techniques through different pathways of their applications.

3.1 Introduction

The construction industry is a major contributor to the gross domestic product (GDP) of a country’s economy (He& Shi, 2019). The issue of the decline of productivity in the construction industry (Stevens, 2014) has been put in the spotlight due to failures to meet ever-changing performance expectations for half a century (Sveikauskas et al., 2016; Green, 2016). Therefore, there is a need to bring productivity out of this deadlocked state since the construction industry, directly and indirectly, impacts the economy (Green, 2016) of both developing and developed countries. As the main aspects of performance, inefficiencies in time, cost and quality in the Iron Triangle not only result in client dissatisfaction, but also negatively impact the economy in a broader sense. In the UK, a pioneer in the construction industry, this issue has caused the authorities to consider construction re-engineering. The construction sector needs an upgraded operating system to allow it to meet the expectation of productivity growth in compliance with the pillars of the Iron Triangle as the primary performance constraints. These constraints were later extended to five criteria, including time, cost, quality, scope and risk (Bronte-Stewart, 2015). Sabet and Chong (2018) defined these criteria as time, cost, quality, stockholder satisfaction and safety: the main aspects of construction performance. The question of how to manage these constraints challenges companies and authorities in the construction industry. New business models and upgraded construction management have been required to eliminate the challenges associated with meeting expected construction performance (McGeorge et al., 2012). An effective project operating system that is supported by technological innovation is at the heart of a better workflow (Changali, 2015). Management considerations and the implementation of advanced techniques have not yet satisfied the requirements for performance achievement. Those measures need to be reinforced by a range of productivity fundamentals that can help to fulfil productivity objectives at different stages of a project. The question arises as to which fundamentals can supplement the capabilities of these advanced techniques.

Hence, this paper addresses a range of productivity fundamentals and clarifies how they play a vital role in meeting performance goals once the required advanced techniques have been implemented. The potential benefits may be useful to: (a) developers of new techniques, who may use this study to establish upgraded technical concepts for the updated productivity criteria linked to project performance; and (b) practitioners who should consider these productivity fundamentals for the effective implementation of advanced techniques.

3.2 Literature Review

3.2.1 Productivity requirements and issues.

The construction sector is a pillar of the GDP of a country. The income derived from the construction industry is a significant proportion of GDP, as are the indirect incomes that arise from marketing and operational services (Richardson, 2014). The inefficiencies arising from the construction sector not only result in client dissatisfaction, but also impact the economy due to low productivity. Lack of an integrated management followed by fragmentation among the stockholders and have been flagged as factors that reduce construction productivity in conventional construction (Bresnen & Marshall, 2000; Ganesan, 2000).

Low construction productivity has always challenged stakeholders and clients. Force (1984) stated that ‘clients need better value from their project, and companies need reasonable profits to assure their long-term future’ (p.10). Development of new strategies is an important task for researchers aiming to improve the industry. Implementation of new techniques and technologies in process development has been important in overcoming the challenge of low productivity. In this regard, fostering commitment between the parties involved in a project appears to be one of the important requirements of the process. Force (1984) stated that embracing change has been identified as the key factor in successfully improving productivity in industry, but that the construction industry has been very resistant to change. According to Force (1984), a series of fundamentals of the project process, such as committed leadership, a focus on the customer’s requirements, process and team integration, a quality-driven agenda and commitment to the different stakeholders, are the radical changes required in the construction industry. These necessary changes are impossible without properly implementing new techniques and technology to increase innovation. Winch (1998, p. 268) stated that ‘the roles of the innovation infrastructure, innovation superstructure and systems integrator are’ the fundamentals of the successful establishment of innovation in the construction industry. Also, effective management of multi-cultural human resources at different levels at job sites is another consideration fundamental to project productivity and success (Enshassi, & Burgess, 1991; Fellows& Liu 2012). Moreover, skilled benchmarking can play an important role in improving a construction project. According to the report (1998) made by Task Force, practising these fundamentals together are the only way to successfully implement new techniques and technologies.

Changali et al. (2015) argue that fast-growing investment, requests for larger shares in megaprojects and poor completion of megaprojects determine the need for new techniques and approaches that are consistent with the productivity expectations for future projects. They believe that a range of measurements made at three stages of a project; namely, concept and design; contract and procurement; and lastly execution, can remove potential weaknesses reducing productivity. Also, Changali et al. (2015) stated that slow decision-making and processes within an organisation can result from inaccurate and poor reporting from team members and stockholders. In fact, this shortcoming impedes communication between stakeholders and prevents prompt action within a project.

Lack of clear contracts are another reason for productivity loss. In this case, the negotiations required to manage any conflicts as they arise are complicated and may be followed by a lengthy dispute resolution process. As different roles and activities are defined at different layers within a project, suitable measures are required to network these roles and control activities to avoid any interference in planning and scheduling (resolution of the issue of fragmentation) (Fellows &Liu, 2012). Short-term planning and taking alternatives to reinforce planning and scheduling are important considerations to keep project progress on track. Further, a consistent management style is central to ensuring that staff contribute their highest capacities and competencies to a project (Enshassi &Burgess, 1991). Inappropriate risk allocation has also been reported as a cause of inefficiencies; not involving stakeholders other than the contractor puts all the responsibility for the project on the contractor.

Previous studies have largely focused on determining the productivity indicators in construction projects from the perspective of value-creating approaches. Cost benefit analysis and return on investment (ROI) have been used evaluate the performance resulting from the implementation of new techniques and technologies. However, no prior research has considered a generic pathway or the interactions between productivity indicators and aspects of construction performance after the implementation of advanced techniques in projects. This paper discusses the pathways through which the new advanced techniques can impact different aspects of performance, and suggests a range of productivity fundamentals that can act as catalysts or reinforcers that contribute to the improvement of the operating system via the implementation of advanced techniques. This paper claims overall project performance to be the output of a function in which potential productivity fundamentals are aligned with the implementation of advanced techniques.

As the literature implies, the factors affecting construction productivity can be identified as delayed schedules, changed orders, materials mismanagement, unstable weather conditions and human performance-related factors. Park (2006) claimed that management considerations and environmental conditions play the determinant roles in estimating productivity in construction. Bassioni et al. (2004) believed that identifying the indicators affecting productivity that interact with new techniques can result in successful productivity improvement. Table 3.1 categorises the factors threatening productivity that have been identified in the literature. It may help developers of new techniques to consider the actions required to eliminate weaknesses in the establishment of future technologies and approaches.

Table 3.1

Potential roots of poor productivity

Potential roots of poor productivity	Sources that contribute to confirm these roots
Poor organisation	El-Razek et al., 2008; Azhar et al., 2008
Inappropriate relationship management and communication among stockholders	Durdyev& Ismail, 2016; Naoum, 2016; Emmitt& Gorse, 2006; Meng, 2012
Ineffective management style	Lavender, 2014; Kazaz& Ulubeyli, 2007
Lack of technical specifications and contract clarification	Jarkas& Radosavljevic, 2012; Jaffar et al., 2012
Lack of skilled crew members and inefficient connection with the crew	Shohet& Laufer, 1991; Islam& Khadem, 2013; Jarkas& Bitar, 2011
Untracked planning/scheduling (poor project control)	Aziz& Hafez, 2013
Lack of risk management allocation	Mills, 2001; Wang et al., 2004
Competencies mismanagement	Singh, 2010; Islam& Khadem, 2013
Lack of upgraded equipment, methods and materials	Alwi, 2003; Ghoddousi et al., 2012; Thomas et al., 2003
Lack of satisfactory working conditions	Abrey& Smallwood, 2014; Hanna & Heale, 1994

Improved construction performance is the result of productivity improvement (Sabet & Chong, 2018). Force (1998) observed the potential for productivity improvement by reducing capital costs, project duration, the number of accidents and employee turnover and staff productivity. Hoehne and Russell (2018) reported that poor construction productivity may be due to fragmentation of stakeholders, contract mismanagement and an opaque marketplace. Therefore, a range of measurements of these strengths and weaknesses can contribute to assessing the overall project performance.

3.2.2 The debate on ROI.

This debate has been raised due to risk of the loss of value of investments. A reasonable ratio of benefit to cost is expected from the ROI perspective. Time, cost, quality, safety and stakeholder satisfaction are the pillars of ROI. Developing the range of objectives is the first crucial step in ROI methodology, which sets out five crucial levels of objectives at the concept and development stages to sell interactive technologies. The objective levels include reaction objectives, learning objectives, application objectives, impact objectives and a final ROI objective (Wagner & Derryberry, 1998). These productivity requirements are the preliminaries for the ROI perspective, and are crucial in developing new techniques and business models. Different models may incorporate various costly stages. As an example, the cost of quality model consists of several layers of quality achievement. This model determines the costs of quality achievement within four areas: prevention costs, appraisal costs, internal failure costs and external failure costs (Lindsay & Evans, 2010; Jafari& Love, 2013).

3.2.3 Emerging advanced techniques for construction projects.

As stated earlier, rethinking construction is necessary to reduce dissatisfaction with overall construction performance. Force (1998, p. 4) identified four factors that are important for resolving the issue of client dissatisfaction, including, ‘committed leadership, a focus on the customer, integrated processes and teams, a quality-driven agenda and commitment to people’. End-user dissatisfaction can originate from a lack of stakeholder satisfaction with the project. Lack of stakeholder satisfaction results in inefficiencies and vice versa, impeding project productivity. How to respond to the interests of stakeholders and manage their reactions within an organisation is crucial when managing stakeholders (Jepsen & Eskerod, 2009). Further, stakeholder commitment regarding competent decisions made during the project improve company performance (Song& Zhang, 2017). Therefore, the need to improve productivity has paved the way for advanced and emerging techniques and technologies, each with their own characteristics. In recent years, advanced techniques, such as prefabrication, automation and IT-based techniques, have drastically altered the construction industry, changing its focus from traditional practice to modern enterprise (Nam et al., 2019).

(Agazzi, 1998, p.2) referred to a technique as ‘a display of practical abilities that allow one to perform easily and efficiently a given activity’. Isman (2012) defined a technique as having the practical knowledge to contribute to a procedure or a system and referred to technology as organising and practically applying knowledge to produce a concrete result. As examples, modern construction is considered a technology Isman (2012), while the lean production and prefabrication contributing to potential modern construction are considered techniques. Therefore, the application of a new technique may be followed by creation of a new technology. The interdependent implementation of these advanced techniques, as well as their concurrent applications under a well-defined, systematic adoption, form potentially value-making leverage for the performance of construction projects (Nguyen & Akhavian, 2019).

Based on ‘productivity improvement strategies’ (Gunasekaran, & Cecille, 1998) three steps can determine whether improvements are achieved by implementing new techniques and technologies: first, setting clear objectives; secondly, putting in place the pathways needed to achieve the objectives; and thirdly, sharing and comparing data to assess performance with other practitioners in the industry.

The ROI perspective has been useful in creating a range of new approaches and techniques, each with their own specific characteristics and particular potential to create improvements. The following sections discuss these functions.

3.2.3.1 Big data.

These newly advanced techniques generate high volumes of useful data that can contribute to improving productivity (Ismail et al., 2018). Therefore, they can be categorised as big data-inspired techniques, which, by definition, deal with the large amounts of information required for decision-making. The term ‘big data’ refers to an industrial revolution brought about by the use of vast amounts of data—characterised by volume, variety and velocity (the 3Vs)—for business improvement, cost optimisation and prediction of revenue (Ismail et al., 2018). The three basic functions of big data are recognition of customer priorities, prediction of market trends and business process optimisation. This third function has been found to be applicable to the construction industry and to improve cost-effectiveness. Cost reduction is the final outcome of the comprehensive information on cost-effectiveness provided by big data-directed techniques and tools. However, this requires a systematic workflow to extract the information applicable to the decision-making process (Bilal et al., 2016). Innovation of new services and products is a priority for reducing costs. An understanding of customer expectations, consumer concerns and market prediction is an essential preliminary of process optimisation—another great outcome of big data, which contributes to the decision-making processes that influence the development of innovation. Process optimisation can be found applicable to the construction industry, which relies on cost-effective solutions. Bilal et al. (2016) believed that the 3Vs of big data can influence productivity streamlining. However, this benefit requires a masterful, systematic workflow to extract constructive materials applicable into the decision-making process (Bilal et al., 2016). Shrestha (2013) declared that a range of diverse data are generated within the phases of construction projects; these data are required to be processed, streamlined and exchanged among stockholders during decision-making. This diversity of data can reflect the 3Vs of big data that configure the pathway towards improvements in efficiency during a building project’s lifecycle (Motawa, 2017). Advanced techniques generate not only a high volume of data, but also effective information that contributes to the improvement of productivity (Ismail et al., 2018).

Therefore, it is claimable that the techniques are aligned with the objectives of big data concept and can be categorised as big data inspired techniques.

The techniques outlined in this section are categorised as big data-based techniques, as their objectives are to provide the project's operating system with sophisticated information.

3.2.3.2 BIM.

A revolutionary emergence, BIM offers numerous precise and practical data to the construction industry, from an improved computer-aided drawing (CAD) model, to the involvement of project stockholders in a multidisciplinary working environment (Eadie et al., 2013). BIM presents considerable potential for coordination, collaboration and integration along with improvements in information flow and data processing that reach beyond the capacity of traditional construction methods (Li et al., 2019).

According to existing literature, Sabet and Chong (2018) listed the leading capabilities (practices) of BIM as planning and scheduling, constructability assessment, 3-D model visualisation, clash detection, measurement and estimation, site management, safety management and operation management—as last, but not least.

Through these constructive practices, BIM has improved the construction industry from different perspectives, enabling stockholders to capture and process information within a project's various stages. Information transformation optimises the project procedure, contributing to perfect completion (Azhar, 2011).

Ismail et al. (2018) declared that BIM is not precisely equal to big data. However, Bilal et al. (2016) claimed that the application of BIM, along with other advanced techniques and devices for procuring data, aligns with big data's mission to flourish within the industry of construction management.

3.2.3.3 Augmented reality.

AR is a technique by which captured images can be manipulated in the same way as they can in reality. In fact, the images can be linked to the real world, occupying the same spatial dimensions (Azuma et al., 2001).

AR originated from virtual reality (VR), which partially but tangibly creates an environment wherein the operability of an object can be sensed and practised in real time to improve human understanding of it (Jiao, 2013). As the high-quality visualisation of details is very effective for reducing the complexity of information (Bilal, 2016), it is claimed that the AR technique accords with big data’s objective to generate information for better decision-making (Olshannikova et al., 2015). For example, AR is capable of being paired with BIM to enable designers to apply more maintainable and sustainable principles to their designs. This point improves facility management at the building operation stage (Khalek et al., 2019).

3.2.3.4 VR.

VR is a technique via which users can experience the real working environment before project completion. This technique offers an ‘interactive 3D graphic, user interfaces, and visual simulation’ (Zyda, 2005, p.25). It has been found to be very useful for improving safety. VR training significantly improves the efficiency and productivity of ‘stone cladding work and cast-in-situ concrete work’, saving the time that would be spent on conventional training (Sacks et al., 2013). They stated that training via VR effectively attracts newcomers’ attention and produces concision. Messner et al. (2003) believed that VR helps trainees to understand certain technical details better. The trainees sensibly address ‘construction sequences, temporary facility locations, trade coordination, safety issue identification, and design improvements for constructability’ (Messner et al., 2003, p.1).

3.2.3.5 Blockchain.

Crosby et al. (2016) defined blockchain as a technique through which not only the databases of records but also all transactions or digital activities are recorded and distributed among stockholders. Once entered, data never can be removed. Belle, (2017, p.280) expressed four characteristics of the blockchain:

> (1) It is public, not owned by anybody, (2) it is decentral, not stored on one single computer but on many computers owned by different people across the world, (3) constantly synchronised to keep the transactions up to date, and (4) secured by cryptography to make it tamper proof and hacker proof.

Turk and Klinc (2017) found blockchains to be capable of improving the construction industry by overcoming lost data and manipulating issues within the life-cycles of projects. 'Smart construction relies on BIM for manipulating information flow, data flow, and management flow' (Zheng, 2019, p.1), which the blockchain can address. The processes of unifying data, maintaining verifiable records and keeping data permanently available make the blockchain relevant to both financial and non-financial schemes (Crosbey et al., 2016) When it comes to the field of construction, the application of a blockchain to a smart contract is a bold move (Zheng et al., 2019). A blockchain can keep an accurate visible history of the actions users have taken across the network (Pilkington, 2016) thereby supporting the smart contract to be secured. All provisions and protocols can be permanently available in a chained structure, with no opportunity of change (Turk& Klinc, 2017). In such a situation, not only can all regulations be supervised, but the duties of users can also be tracked.

3.2.3.6 Laser scanning.

Laser scanning is a technique by which actual, accurate data from an as-built situation are retrieved by scanning the work's progress or status. The data can then be used to evaluate quantities of work and to report progress (El-Omari &Moselhi, 2008) or for decision-making purposes (Goedert & Meadati, 2008). El-Omari and Moselhi (2008) believed that the accurate reporting of progress to management is a determinant action in the effective delivery of projects. The chance of a proper report is higher through 3D laser scanning, which is capable of highly accurate reporting through the provision of precise data. Su et al. (2006) observed this technique to be very practical for improving the efficiency of urban underground works, where working spaces were restricted in terms of visibility and movement. Randall (2011) described laser scanning as a complementary measure for BIM that could influence the various phases of projects, including programming, planning, design, construction, operation and maintenance.

3.2.3.7 Artificial intelligence techniques.

In simple words, AIs are techniques whereby human perceptions can be transferred to machines, allowing them to perform the way humans supposedly would in complicated situations (Chen et al., 2008). AI makes industries more efficient and effective, allowing intelligent automatic machines to ‘analyse the human’s thinking system and reflect the same to reality’ (Dede et al., 2019, p.1). This technique enables automatic machines to mimic human behaviours and operate intelligently (Nau, 2009). Further, AI can refer to smart software, facilitating better technical information, management and collaboration fields (Anumba et al., 2002). Therefore, the software directing robotic machinery can also be considered AI. Bose (2018) discussed three main areas in which revolutionary AI has intervened. These areas are (1) quicker and more confident decision-making, (2) immediate accessibility and practical insights originating from big data and (3) protection of susceptible data.

AIs have the potential to rapidly and imminently affect the construction industry by tackling industrial issues without physically involving humans in a complex working system (Joes et al., 2018). Joes et al. (2018) listed a range of potential fields within the construction industry that AIs could influence, including cost overrun, design optimisation, risk mitigation, planning, site productivity, safety, labour shortages, prefabrication, data generation and building operation.

3.2.3.8 Off-site manufacture (OSM).

OSM is a technique offering a combination of prefabricated components and on-site activities. The components are either erected to shape a constructed object or attached to in-situ built components (Blismas &R. Wakefield, 2009). In fact, 'the off-site components are produced in a controlled manufacture environment and then transported and positioned onto a construction site' (Sabet& Chong, 2019, p.207). In 2017, the Sustainable Built Environment's National Research Centre (SBEnrc) declared that OSM was capable of providing the construction industry with optimal opportunities over the next decade. These opportunities are significantly aligned with demands for affordable housing, set to double by 2021. Sabet and Chong (2018) listed a range of OSM attributes arising from these opportunities: automation and series production, faster investment return, employment opportunities, sustainability and safety.

3.2.3.9 Automation.

Automation refers to a technique by which a procedure or a cycle of processes is carried out with minimal human involvement (Groover, 2014). This technique makes industries more efficient and effective by applying software and hardware to complete tasks automatically. Through this highly beneficial technique, equipment, machinery and processes are operated via controlling systems in complex situations. However, sometimes, a controlling system fails as a consequence of human-related error and any potential benefit is transformed into a loss or even a disaster (Lee& See, 2004). Lee and See (2004) believed that automation dramatically improves human performance and safety, provided that accurate data are entered into the system and its transformation is reliable. Automation has not only been observed to optimise construction site productivity but is also capable of promoting the mass production of prefabricated construction components in factories (Neelamkavil, 2009).

3.2.4 Productivity indicators.

Clear objectives are necessary to drive a dramatic improvement in productivity. These must be followed by constructive strategies, milestones and the identification of productivity indicators (Force, 1998). These indicators must reflect project inputs and contribute to project progress as process outputs. Productivity is ‘a relationship (usually a ratio or an index) between output (goods and/or services) produced by a given organisational system and quantities of input (resources) utilized by the system to produce that output’ (Hannula, 2002, p. 59). Force (1998) believes that productivity indicators must be related to time, cost, quality and predictability.

Sabet and Chong (2019, p.4) explained that ‘input refers to materials ($), personnel (P-H), and equipment ($) put into the projects while output refers to production unit’. Construction progress can be simulated for the production unit on construction sites. Construction activities are ranked as high cost business activities. Thus, productivity achievement refers to the minimum input needed to achieve a reasonable output (Huang et al., 2009). In the current paper, the terms productivity and performance and their borders within the construction field have been discussed as a preliminary to identification of productivity indicators. “Performance perspective from a broad sense can be followed by productivity perspective in a narrow sense” (Sabet & Chong, 2019, p.4). This claim suggests that productivity can be deemed a consequence of performance. However, Dozzi and AbouRizk (1993) stated that the term productivity equals performance.

Various indicators of productivity and performance have been reported. Socio-economic conditions have been identified as the reason for this variety across different countries (Hassan et al., 2018). The indicators have been divided into quantitative and qualitative categories; quantitative indicators can be physically measured (numerical) using measurement scales. For example, these indicators might be scaled via a report on costs, material usage, completion of a proportion of activities and the number of crew members. Qualitative indicators refer to those that cannot be tangibly observed and scaled. These indicators do not show the exact data for a project trend but offer a description of a situation (e.g., a safety report) (Cox et al., 2003). Sabet and Chong (2019) offered a comprehensive conceptual framework that categorised KPrIs as company characteristics, labour, materials, management, documentation and regulations, machinery, contract conditions, IT involvement, engineering and external circumstances. Among other indicators, improved productivity is guaranteed by an appropriate management style (Enshassi & Burgess, 1991; Fellows, & Liu, 2012) and the implementation of well-structured techniques (Winch, 1998).

3.3 Methodology

For this scoping review, a micro-to-macro method was used to assemble the relevant literature. Each dimension of this two-dimensional view interacts with the other for a more efficient analysis (Wagner &Derryberry, 1998) of the requirements for the development and application of advanced techniques. Here, the micro dimension examines the range of productivity fundamentals as the supplementary foundation on which advanced techniques should be applied, while the macro dimension focuses on the stages at which these fundamentals need to be applied. Further, a holistic understanding of the selected advanced techniques is provided through the literature review. This review method links evidence retrieved from the literature to justify the designated objectives. This method is particularly relevant in the case of new topics on which the literature is scarce (Sabet & Chong, 2019). Table 3.2 shows the sources reviewed to evident this paper’s claim. Also Figure 3.1 shows how the review method was developed in this study.

Table 3.2 *The supportive sources for this paper*

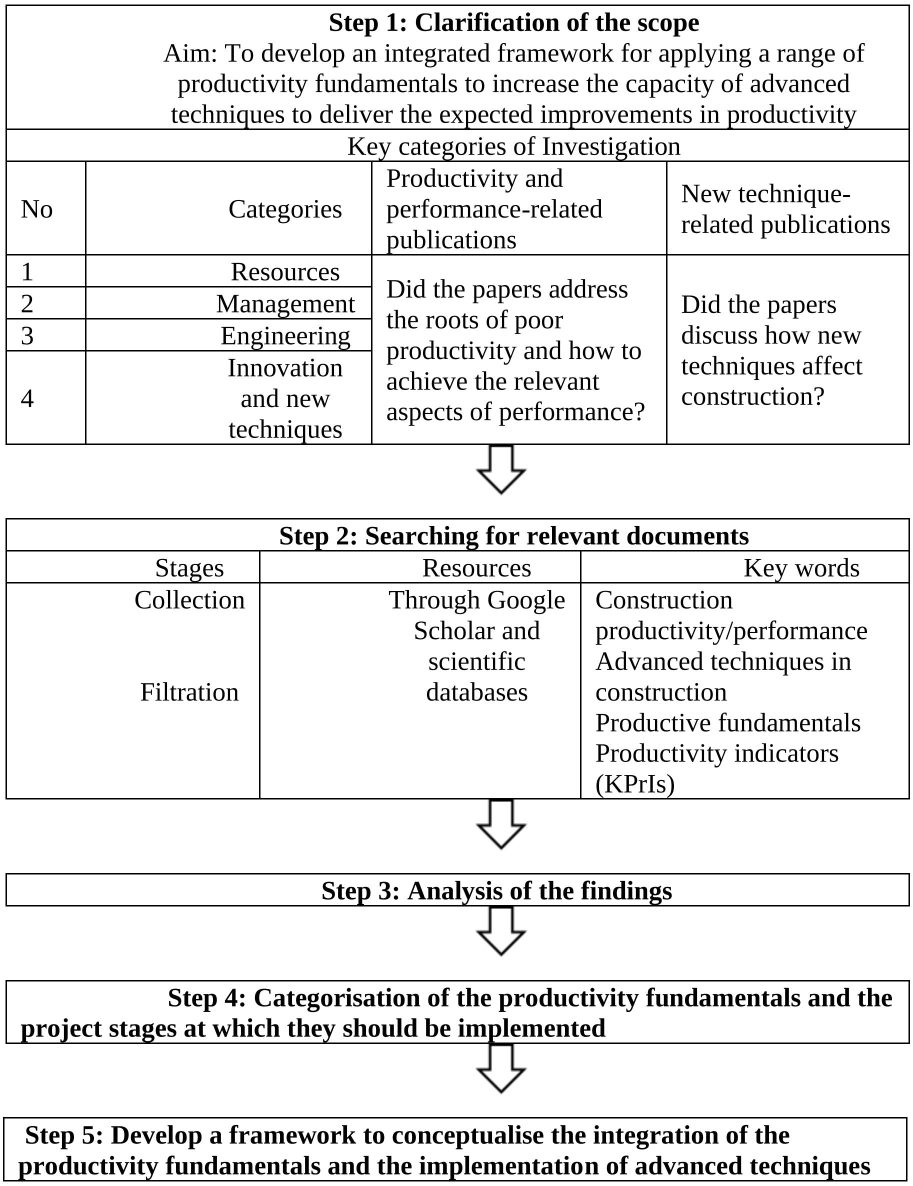
NO	The sources of the current paper	The sources contributing to Productive fundamentals	The sources confirming advanced technique definition and their applications for performance
1	W. He & Y. Shi (2019)	X	
2	M. Stevens (2014)	X	
3	L. Sveikauskas et al. (2016)	X	
4	B. Green (2016)	X	
5	M. Bronte-Stewart (2015)	X	X
6	P. Sabet, H.Y. Chong, (2018)	X	X
7	D. McGeorge & PXW. Zou (2012)	X	
8	S. Changali et al. (2015)	X	
9	D. Richardson (2014)	X	
10	M. Bresnen & N. Marshall, (2000)	X	
11	S. Ganesan, (1984)		
12	T.Force (1998)	X	
13	G. Winch (1998)	X	
14	A. Enshassi, & R. Burgess, (1991)		X
15	R. Fellows, & A. M. Liu, (2012)		X
16	H.S. Park, (2006)		X
17	H.A. Bassioni et al. (2004)		X
18	M. Abd El-Razek et al. (2008)		X
19	N. Azhar et al. (2008)	X	
20	S. Durdyev & S. Ismail, (2016)		X
21	S. G. Naoum, (2016)		X

NO	The sources of the current paper	The sources contributing to Productive fundamentals	The sources confirming advanced technique definition and their applications for performance
22	S. Emmitt & C. Gorse, (2006)		X
23	X. Meng, (2012)		X
24	S. D. Lavender, (2014)	X	
25	A. Kazaz & S. Ulubeyli, (2007)		X
26	A. M. Jarkas & M. Radosavljevic, (2012)	X	
27	N. Jaffar et al. (2011)		X
28	I. Shohet & A. Laufer, (1991)	X	
29	M. A. Islam, & M. Khadem, (2013)		X
30	A. M. Jarkas & C. G. Bitar, (2011)		X
31	R. F. Aziz & S. M. Hafez, (2013)		X
32	A. Mills, (2001)	X	
33	S. Q. Wang et al. (2004)	X	
34	S. P. Singh, (2010)	X	
35	S. Alwi, (2003)		X
36	P. Ghoddousi & M. R. Hosseini, (2012)	X	
37	H. R. Thomas et al. (2003)		X
38	M. Abrey & J. Smallwood, (2014)		X
39	A. Hanna & D. G. Heale, (1994)	X	
40	E. D. Wagner & A. P. Derryberry, (1998)	X	
41	D. Samson, & M. Terziovski, (1999)	X	
42	A. Jafari & P. E. Love, (2013)	X	
43	Jepsen and Eskerod (2009)	X	
44	Song et al. (2017)	X	
45	Nam et al. (2019)		X
46	E. Agazzi, (1998)		X
47	Isman (2012)		X
48	Nguyen & Akhavian (2019)		X
49	Gunasekaran & Cecille (1998)	X	

NO	The sources of the current paper	The sources contributing to Productive fundamentals	The sources confirming advanced technique definition and their applications for performance
50	S. A. Ismail, S. Bandi, & Z. N. Maaz, (2018)		X
51	M. Bilal et al. (2016)		X
52	Shrestha (2013)		X
53	Motawa (2017)		X
54	R. Eadie et al. (2013)		X
55	Li et al. (2019)		X
56	S. Azhar (2011)		X
57	R. Azuma et al. (2001)		X
58	Jiao et al. (2013)		X
59	Olshannikova et al. (2015)		X
60	Khalek et al. (2019)		X
61	M. Zyda (2005)		X
62	R. Sacks et al. (2013)		X
63	J. I. Messner et al. (2003)		X
64	M. Crosby et al. (2016)		X
65	I. Belle (2017)		X
66	Z. Turk & R. Klinc (2017)		X
67	R. Zheng et al. (2019)		X
68	M. Pilkington, (2016)		X
69	S. El-Omari & O. Moselhi, (2008)		X
70	J. D. Goedert & P. Meadati, (2008)	X	
71	S. El-Omari & O. Moselhi, (2011)	X	X
72	Su et al. (2006)		X
73	Randall (2011)		X
74	S. H. Chen et al. (2008)		X
75	Dede et al. (2019)		X
76	D.S. Nau (2009)		X
77	C. Anumba et al. (2002)		X
78	S. Bose, (2018)	X	
79	Jose et al. (2018)		X
80	N. Blismas &R. Wakefield, (2009)		X
81	Sabet & Chong (2019)	X	X
82	SBEnrc (2017)		X
83	M.P. Groover (2014)		X

NO	The sources of the current paper	The sources contributing to Productive fundamentals	The sources confirming advanced technique definition and their applications for performance
84	J.D. Lee & K. A. See (2004)		X
85	J. Neelamkavil (2009)		X
86	M. Hannula (2002)	X	
87	A. L. Huang et al. (2009)	X	
88	S. P. Dozzi, & S. M. AbouRizk, (1993)	X	
89	A. Hasan et al. (2018)	X	
90	R. F. Cox et al. (2003)	X	
91	S. Golnaraghi et al. (2019)	X	
92	H. Elnaas et al. (2014)		X
93	J. Lessing et al. (2005)		X
94	C. L. Pasquire & Connolly (2002)		X
95	S. Durdyev, & S. Ismail, (2019)		X
96	L. Ding et al. (2014)		X
97	Kang et al. (2007)		X
98	J. Li et al. (2014)		X
99	N. Lee et al. (2014)		X
100	L. Chen & H. Luo, (2014)		X
101	S. Khoshnava et al. (2012)		X
102	K. Sulankivi et al. (2010)		X
103	X. Wang & P.E. Love (2012)		X
104	P. Smith (2014)		X
105	X. Li et al. (2018)		X
106	J. Wong et al. (2014)		X
107	A. Behzadi, (2016)		X
108	W. Shen et al. (2010)	X	
109	Z. Pan et al. (2006)		X
110	D. Zhao & J. Lucas (2015)		X
111	Y. Fang et al. (2014)		X
112	R. Oudshoorn (2018)		X
113	D. Gleason (2013)		X
114	D. Huber et al. (2010)		X
115	D. Tapscott &A. Tapscott (2017)		X
116	M. Kassem et al.(2018)		X

NO	The sources of the current paper	The sources contributing to Productive fundamentals	The sources confirming advanced technique definition and their applications for performance
117	W. Lu et al. (2015)		X
118	J. Brandenburger et al. (2016)		X
119	S. F. Wamba, S. Akter, & M. De Bourmont, (2019)		X
120	A.Ø. Sørensen, N. Olsson, and A.D. Landmark, (2016)		X
121	C. Balaguer & M. Abderrahim, (2008)		X
122	T. Hegazy et al. (1999)	X	
123	A. O. Elfaki et al. (2014)		X
124	J. Peleska (1996)	X	
125	P. X. Zou et al. (2007)	X	
126	P. Meadati (2009)		X
127	Y. Ji et al (2019)		X
128	A. T. Gurmu & C. S. Ongkowijoyo, (2020)	X	



Step 1: Clarification of the scope

Aim: To develop an integrated framework for applying a range of productivity fundamentals to increase the capacity of advanced techniques to deliver the expected improvements in productivity

Key categories of Investigation

No	Categories	Productivity and performance-related publications	New technique-related publications
1	Resources	Did the papers address the roots of poor productivity and how to achieve the relevant aspects of performance?	Did the papers discuss how new techniques affect construction?
2	Management		
3	Engineering		
4	Innovation and new techniques		

Step 2: Searching for relevant documents

Stages	Resources	Key words
Collection Filtration	Through Google Scholar and scientific databases	Construction productivity/performance Advanced techniques in construction Productive fundamentals Productivity indicators (KPrIs)

Step 3: Analysis of the findings

Step 4: Categorisation of the productivity fundamentals and the project stages at which they should be implemented

Step 5: Develop a framework to conceptualise the integration of the productivity fundamentals and the implementation of advanced techniques

Figure 3.1. The procedures used in the scoping review.

The first step was to identify the root causes of poor productivity in the construction industry. Recent advanced techniques that affect project operating systems were examined to establish the pathways through which the different aspects of performance can be improved. To this end, the areas of resources, management, engineering and innovation were searched. The next stage involved finding relevant sources by collecting and filtering documents to retrieve credible evidence to substantiate the arguments made in this paper. Documents were identified by searching Google Scholar and scientific databases using keywords, including ‘construction project stages’, ‘construction productivity’, ‘construction performance’, ‘advanced techniques in construction’ and ‘productivity considerations’. Next, the abstracts of the articles identified scanned to assess the relevance of the paper, and those of interest were evaluated to develop a clear understanding of the issues and requirements for construction productivity, productivity fundamentals, the stages at which these fundamentals should be applied and the capabilities of the relevant advanced techniques. The research questions were then developed, asking what the state of construction productivity and performance is, and how to reinforce the implementation of advanced techniques to fulfil the project objectives and meet the expected return.

3.4 Findings and Data Analysis

The highly dynamic nature of construction projects can be challenging to their progress (Golnaraghi et al., 2019). Difficult situations can be exacerbated if advanced techniques are not fundamentally supported in an organised and proper manner to fulfil their objectives. He and Shi (2019) believed that an ‘effective construction organisation plan’ is central to a construction optimisation model that results in project performance. Sabet and Chong (2018) have claimed that the debate around productivity is aligned with that of performance in the construction industry. They state that the expected outcome of performance in the boarder sense is achievable through the improvement of productivity indicators in the narrow sense. This means that performance achievement is not straightforward, unless the required agents involved in productivity play a vital role in influencing a project’s work flow.

Table 3.3 gives a summary of credible sources indicating how the recent highlighted advanced techniques have successfully influenced the aspects of construction performance so far.

Table 3.3 *Advanced techniques and their effects on construction projects*

Advanced techniques	Performance aspects	Ways in which construction projects can be influenced	Sources
Off-site manufacture	Time	Since better quality control can be achieved in a more controlled working environment (OSM-based project), the chance of any rework disturbing planning and scheduling in a project is minimised	SBEnrc, 2017; Elnaas et al., 2014; Lessing et al., 2005
	Cost	24-hour availability of materials in factory stock reduces the time needed for ordering and transferring materials and thus the total project time.	SBEnrc, 2017; Pasquire & Connolly, 2002
	Quality	Better monitoring of construction processes to produce the construction elements in a controlled environment leads to improved achievement of specifications, which contributes to quality performance	SBEnrc, 2017; Lessing et al., 2005
	Safety	Safety considerations are easier to observe in a factory environment where prefabricated construction components are produced. Occupational health and safety principles can efficiently and effectively imposed and monitored in a controlled work environment	Blismas & Wakefield, 2009; SBEnrc, 2017
	Stakeholder satisfaction	Stakeholder satisfaction is achievable by systematic adoption of advanced techniques. Respondent satisfaction has been reported for ‘reduced construction periods, on-site construction and labour costs and improved quality, there still is room to overweight safety and waste subjects of OSM-based projects and compare them with that of non-OSM-based projects. It is mentionable that the level of adoption and how the adoption should be organised can play a determinant role in stakeholder satisfaction’	Durdyev & Ismail, 2019, p.1
Building information modelling	Time	The coincidence of 3-D model of designs in a virtual environment can reveal any potential interference between building activities, limiting the chance of any time-consuming modifications of initial planning and scheduling while the project is in progress.	Ding et al., 2014; Kang et al., 2007
		Through a virtual model supported by an information-sharing platform in BIM, the parties involved in a project can be linked	

		together to evaluate any potentially conflicting situations, and a rapid decision can be made in the case of any confusion that may affect project progress	
	Cost	Limiting the chance of rework and safety issues directly influence cost performance. In addition, a BIM model equipped with planning and scheduling tools enables the relevant experts to optimise resource management, which helps optimise cost performance	Hou et al., 2014
	Quality	A high-quality virtual model rapidly clarifies information related to materials specifications and the delivery details of certain activities, such as the dispatch and assembly of prefabricated components at the construction site. This limits the chance of poor performance, contributing to improved quality assurance	Lee et al., 2014
	Safety	Dynamic safety analysis can be practised via the virtual site model offered by BIM. Modelling certain operations, such as cranes and plants, improves safety management. A virtual site layout contributes to the effective management of safety considerations	Chen& Luo, 2014; Khoshnava et al., 2012; Sulankivi et al., 2012
		Greater practical clarification is possible by using a virtual environment to improve workers' knowledge, thereby avoiding potentially hazardous situations	
	Quality	By reviewing the processes involved in certain activities with the workforce, the chance of errors or defect in the end product can be limited	
	Stakeholder satisfaction	Easy sharing of information via BIM can contribute to stakeholder satisfaction as they can better understand the other parties' work scope and processes and coordinate their activities accordingly, limiting the chance of potential ambiguities or interference. This theme optimises multidisciplinary coordination and provides a better collaborative environment	Chen& Luo, 2014; Wang& Love, 2012; Smith, 2014; Li et al., 2019
	Cost	The BIM model has excellent capability for determining measures and estimations of site activities. Highly accurate estimation could be offered accordingly, thus reducing excess costs	
	Cost	The optimal operations of cranes and trucks can be modelled in a BIM, and operators advised accordingly to achieve efficient performance. This also optimises the energy resources necessary to operate the site machinery efficiently	

Augmented reality	Time	Time performance is crucial for the implementation of a site schedule. Visually monitoring project progress so that as-built elements can be compared with the as-planned form of the elements can contribute to optimal schedule monitoring, improving time performance. AR provides practitioners a model of the actual site in a virtual environment to compare with the as-built components, which allows quicker inspections and improves decision-making processes	Li et al., 2018
	Cost	AR limits the chance of misinterpreting drawings and exchanging imprecise data. These factors are the main source of time and cost overruns	Wang et al., 2014
	Quality	AR supports automation, which allows optimum operation by the user and minimises defects of operation	
	Safety	An AR system allows practitioners to make virtual site visits. This can contribute to safety performance by highlighting any unseen potential threats without an actual inspection	
	Stakeholder satisfaction	Effective communication and information exchange between the parties involved in the project contributes to stakeholder satisfaction. The additional visualisation capability of AR and the ease of access to information and sharing information via lightweight devices improves stakeholder satisfaction	Behzadi, 2016
Virtual reality	Time and cost	Measures such as training the workforce in a virtual environment and simulating certain activities related to quality improvement leads to effective defect management via VR. This minimises the chance of overlooking any requirements or specifications consuming, which can be costly and time-consuming to rectify	Shen et al., 2010
	Quality	Machine and equipment operators can be highly trained before they start work on the site. The wider workforce can be trained for certain activities through e-learning in VR. For example, steel erection and the placement of installation elements can be modelled in VR. Therefore, a VR platform can improve the quality of work	Pan et al., 2006; Zhao& Lucas, 2015
	Safety	Training of the workforce is a major concern before beginning construction. VR provides an effective platform for training in a virtual environment	Fang et al., 2014
	Stakeholder satisfaction	Detailed visualisation via VR provides all parties with a better understanding of the expectations of others and how to better cooperate throughout the project. This enables	Oudshroom, 2018

		a dynamic process for the protection of key values, openness between parties, and competitive progress	
Laser scanning	Time	In the absence of information on as-built elements, laser scanning contributes to decision-making by offering the information required for the existing components or building to plan any changes or renovations	Gleason, 2013; Huber et al., 2010
		Laser scanning offers accurate data for the production of documentation via capturing and recording construction progress (as-built preparation). The risk of the production of faulty documentation that may offer erroneous information is limited. The identification of faults would take time	Goedert & Meadati, 2008
	Quality	The data offered by laser scanning can be used to monitor and evaluate construction progress if it is in compliance with the specifications as per the drawings. This contributes to quality assurance	Gleason, 2013; Huber et al., 2010
	Cost	Laser scanning is useful for measuring the materials required and accurate calculation of materials orders, limiting the chances of waste	El-Omari & Moselhi, 2008
Blockchain	Stockholder satisfaction	Modern management encourages the architecture, engineering and construction industry to accelerate digitalisation in architectural and engineering procedures, in tender and contract ventures and even during prefabrication for use in construction sites. The blockchain eliminates any chance of data loss and manipulation that may necessitate additional costs through data restoration. Thus, the potential for disputes among the parties involved in a project would be limited	Belle, 2017; Tapscott et al., 2017
	Time and cost	Quick and reliable access to data and information is possible by referring to the decentralised blockchain database. This not only saves transactional data costs, but also develops a trusting environment for collaboration	Kassem et al., 2018
Big data	Time, cost and stockholder satisfaction	Big data-based techniques tangibly affect waste management optimisation that contributes to project performance. These techniques reinforce the reliability of indexes developed for performance measurement. The waste management rate as a reliable index is one example resulting from the application of big data that has created a benchmark for project performance in Hong Kong	Lu et al., 2015; Bilal et al., 2016
	Quality	Simple and fast access to high resolution data to monitor quality is an output of big data-	

		mining techniques. Quality can be effectively tracked by integrating reliable data from various sources	Brandenburger et al., 2016; Wamba et al., 2019; Sørensen et al., 2016
Automation and AI	Time and cost	A high volume of complicated construction-related jobs can be successfully accomplished within a very much shorter period using automatic robots as hardware and tools. Further, smart software can be used to optimise certain processes (e.g., resource allocation and levelling) and to produce reliable data. The chance of any errors resulting in delays and costly reworking is limited by automation. However, additional costs may be incurred as a result of its application	Balaguer & Abderrahim, 2008; Hegazy, 1999
	Time and stockholder satisfaction	Some AI agents are capable not only of providing technical information, such as cost estimation, but also of leveraging collaborative environments by solving time and distance issues. In fact, smart software tools provide stockholders with effective communication tools	Elfaki et al., 2014; Anumba et al., 2002
	Safety	Complicated procedures and substantial physical activities create a significant risk of human error that results in injury. Automation considerably eliminates situations in which crew members may become injured	Peleska, 1996

3.5 Integrated Framework

Based on the explanations given in Table 3.3, each technique is able to influence certain KPrIs only. The uncovered KPrIs appear as devaluing agents for the techniques to meet the expected productivity improvement. In other words, even though the productive capabilities of the techniques that can constructively impact the project productivity, the potential gap contradictory appears that entirely disrupts the performance achievement.

A range of productivity fundamentals are necessary over the lifecycle of a project to improve productivity via the implementation of these advanced techniques. These fundamentals are complementary, and can reinforce the capacity of advanced techniques to increase productivity. Integration management is essential for the implementation of the essential elements of productivity and advanced technique. A successful establishment of management relies on close communication between project participants throughout a project's lifecycle (He & Shi, 2019). 'The life cycle of a construction project is normally divided into a few stages, including conceptual (feasibility), design, construction, and operation stages' (Zou et al., 2007, p.6030. Meadati (2009) includes 'planning, design, construction, operation and maintenance, and decommissioning' in the construction project lifecycle. A range of productivity fundamentals have been identified in the literature as complementary to the capabilities of the new advanced techniques. These fundamentals can be potentially be applied during the concept and design, contracting and procurement, and execution stages of a construction project (see Table 2.4).

Table 3.4 *Productivity fundamentals*

Productivity fundamentals	Relevant project stages
Focus the value of the project only on what is required.	Concept and design
Maintain a lifecycle concept of both construction and operation costs.	
Evaluation of alternative scenarios during project planning to overcome unexpected issues.	
Consider site conditions to optimise design.	
Involve modular elements and standardisation during the design.	
Stakeholder involvement in the design phase.	
Optimisation of engineering procedures.	
Share risk between all stakeholders and reflect this in the contract.	Contracting and procurement
Develop efficient compensation and variation request.	
Align the profits of the contractor and the owner as an incentive for early completion.	
Clarify the need for costly items to the owner.	
Updating and adjustable planning for micro-plans in case of overlooked requirements and troubleshooting.	Execution
Employ prefabricated components.	
Consider energy saving strategies.	
Apply waste minimising strategies.	

The integrated framework shown in Figure 3.2 attempts to conceptualise the productivity fundamentals that need to be applied to support the implementation of advanced techniques. A range of productivity fundamentals (listed in Table 3. 4) can be applied throughout at least three stages of a project (concept and design, contracting and procurement, and execution) once one of the advanced techniques is implemented. To depict it, Figure 3.2 reflects that productivity indicators can be improved by the potential capabilities of new advanced techniques that can be reinforced with a range of productivity fundamentals. The productivity fundamentals and the advanced techniques directly and indirectly impact the categories of KPrIs, as highlighted in the process stage in Figure 3.2. The pathways through which the aspects of performance are improved, have been discussed in Table 3.3. Overall, project performance depends on both practising the fundamentals and the capabilities of the advanced techniques at the pre-construction and construction stages.

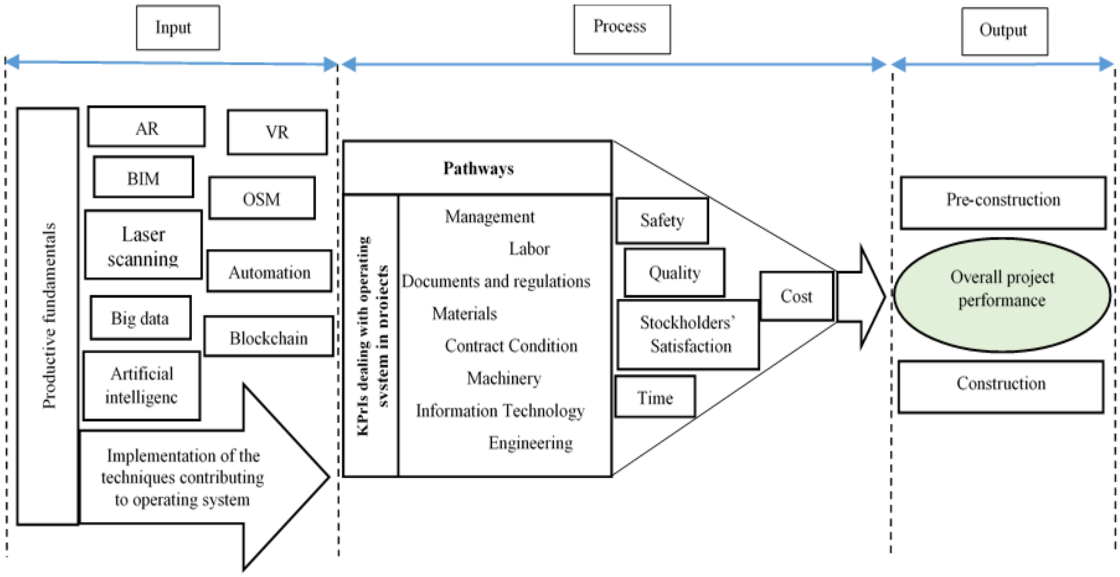


Figure 3.2. Productivity fundamentals to reinforce advanced techniques.

This paper theorises an enriched foundation with a range of productivity fundamentals that the new advanced techniques can be drawn on. The paper presents a conceptualisation of a productivity–performance network with the techniques necessary for achieving reasonable overall project performance, and also addresses the stages at which these fundamentals can be employed to realise potential improvements.

3.6 Discussion and Conclusion

The call for improved construction productivity implies that efforts toward improvements in the construction industry have not fulfilled expectations. Exploring new ways of achieving improvements requires the identification of weaknesses and strengths, and offering practical strategies that align with the pace of the evolution of technology. The implementation of advanced techniques in the construction industry is essential for project success (Ji et al., 2019) in such a competitive business world. Aziz and Hafez (2013) stated that ‘Over the past 40 years’, although several advanced techniques that contribute to modernisation of the construction, the expected efficiency level followed by the required productivity have not been satisfied. Advanced techniques have emerged to satisfy stockholder and end-user demands for productivity. However, these techniques are not capable of addressing all productivity indicators. Further, the lack of conditions in which these techniques may flourish diminishes their capacity. These conditions are referred to as productivity fundamentals in this paper. Awareness of the productivity fundamentals required to reinforce the implementation of advanced techniques is necessary for practitioners. Developing new, consistent and advanced techniques with higher capacities to meet productivity expectations is the target of construction management. Our micro-to-macro methodology was saturated by scoping review. The scoping review (Figure 3.1) of 128 credible sources (Table 3.2) was undertaken to develop a holistic understanding of the productivity requirements in the construction industry and clarify how the new advanced techniques impact the broader scale of productivity and performance. Table 3.3 summarises how these advanced techniques contribute to project operating systems. It highlights that each technique has its own characteristics that need to be paired with a range of productivity fundamentals. Higher productivity is dependent on better project operating systems. What fundamentals, and how to apply them, to improve productivity and achieve better performance may be a headline in the construction industry. A hundred credible sources, including journal articles and several industry reports, were analysed to provide the evidence to substantiate the arguments presented in this paper. This research highlighted the root causes of poor productivity (Table 3.1). The contributions of the common advanced techniques to project performance were summarised (Table 3.3), followed by a range of productivity fundamentals (Table 3.4). Finally, a conceptual framework (Figure 3.2) to conceptualise how to equip a new advanced technique to maximise their influences on project performance. It was shown that the KPrIs categories could be merged into the aspects of performance (See Process section in Figure 3.2). Section 1 shows that the advanced techniques need to be supported by productivity fundamentals. Applying these techniques, along with the productivity fundamentals is key to improve operating system for overall performance. The potential for successful implementation refers to the pathways outlined in this paper supported by productivity fundamentals. Thus, by offering a more analytical perspective, this paper has addressed the range of productivity fundamentals that operate throughout all three stages of a project: concept and design, contracting and procurement, and execution. The construction industry would dramatically benefit from new advanced techniques that are based on the productivity fundamental categories. Figure 3.2 conceptualised performance achievement at the pre-construction and construction stages through the range of fundamentals that can be integrated to practice these techniques. Further investigation to highlight the degree of impact of the productivity fundamentals in an empirical study is recommended.

3.7 Limitations of the Research

The role of qualified craft/ skilled workforce availability that lies in labour productivity (Richardsone, 2014; Sveikauskas et al., 2016) as well as the management style of them (Gurmu & Ongkowijoyo, 2020) are inseparable from the construction productivity theme. The role of newly emerged techniques and the adopted appropriate technique are the other drivers that affect construction productivity. The scope of this paper focuses on the role of newly emerged techniques in the productivity only, which excludes the aspect of workforce availability.

Chapter 4: A Conceptual Hybrid OSM–BIM Framework to Improve Construction Project Performance

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Abstract

Performance improvement has always been an important agenda in the construction industry. Newly emerged concepts such as off-site manufacturing (OSM) and Building Information Modelling (BIM) have been revolutionary movements in the construction industry. However, these methods have not yet fulfilled their full potential, in practice. These techniques can be independently applied in construction projects, but their integrated application would contribute to the fulfilment of their potential to truly benefit the industry. Hence, a new hybrid OSM–BIM system (HOBS) is proposed for performance improvement. This paper aims to review the current state of BIM and OSM techniques to conceptualise a hybrid OSM–BIM framework that formulates their potential interactions and enhances performance in construction projects. An extensive literature review will be conducted to meet the following objectives: (a) to highlight construction performance variables as the targets to be affected by the two techniques; (b) to discuss the standalone attributes of each technique that contribute to the overall project performance. The overall performance is considered because the constructive capabilities and attributes can support and equip a project from in conception level to the construction level. The current paper is expected to not only lay the foundation for exploring interactions to improve the performance of this system through planning and managerial stages, but to also provide solid evidence to encourage professionals and project owners to adopt it. Therefore, client demand will increase, which is vital to the deployment of the system in the construction industry.

Keywords: OSM and BIM framework, OSM capabilities, BIM capabilities, OSM and BIM interactions, construction performance.

4.1 Introduction

Fragmentation in construction projects has been recognised as the root of inefficiency. The need for the resolution of these inefficiencies has paved the way for the emergence of information technologies (ITs). The construction industry has experienced three eras in IT: computerised drafting, electronic and internet contacting tools and techniques and tools integration (Arnold & Javernick-Will, 2012). In recent decades, professionals and authorities have strongly focused on improving data sharing and collaboration among project stockholders with IT (Zhu & Augenbroe, 2006). However, the individual adoption of IT techniques has not met the expected productivity and performance level of projects in response to the high demand of housing. The market is still calling out for productivity and performance. Along with using new IT applications, some researchers recommended taking a different point of view and argue for the integration of other value-making considerations and concepts, through IT(Ahmad, Russell, & Abou-Zeid, 1995).This integration focuses on fulfilling and supplementing IT; for example, linking stockholders and crews, in addition to accelerating the achievement of other concepts (Segerstedt & Olofsson, 2010). Building information modelling (BIM) and off-site manufacturing (OSM) are the new techniques that have attracted researchers' attention. It has been suggested that these two techniques are capable of supplementing each other to improve the construction industry (Abanda, Tah, & Cheung, 2017). The limited literature in this area encourages more research on the deal between OSM and BIM. There are a limited number of studies discussing the potential contribution of the two techniques.

This article aims to investigate the standalone attributes of the two techniques, from the view of project performance, to propose a method for identifying potential potential interactions between the two techniques. The observation and evaluation of other aspects of new achievements can reveal evidence of practicality, which can encourage the users to adopt the technology. This is particularly useful in the construction industry, which is resistant to change. The current paper is based on the following questions: ‘What are the capabilities supporting the successful establishment of a hybrid OSM–BIM system?’; ‘To what extent do those capabilities satisfy the aspects of overall project performance?’; and ‘What are the barriers against the successful establishment of the system?’ Therefore, this paper hypothesises that some capabilities of the two techniques overlap to supplement each other. Figure 4.1 shows the overall hypothesis.

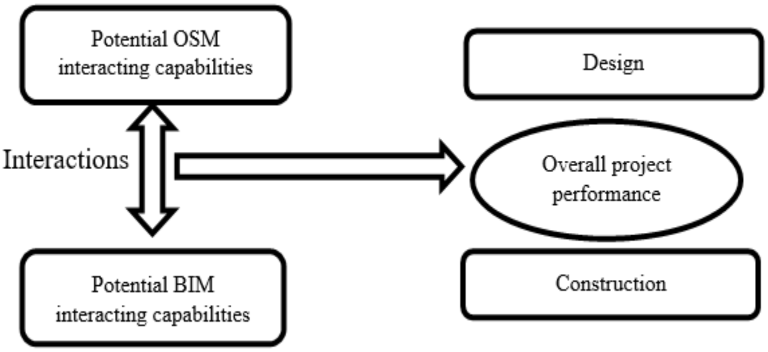

Figure 4.1. The general feature of the hypothesis.

This paper is a part of larger research to develop a pathway that leads to practical interactions and the systematic adoption of this new system for future OSM construction projects.

4.2 Scoping Review

Three scopes, namely BIM, OSM and performance in construction, were considered to gather the information required for the study. The keywords used to search the articles were ‘building information modelling’, ‘off-site manufacture’, ‘performance in construction’ and ‘potential BIM/OSM interactions’. The questions by which the papers were selected were ‘Did the paper address BIM capabilities and OSM attributes?'; 'Did the paper discuss its implementation?'; 'What are the aspects of project performance in the construction industry and how are the aspects achieved through OSM and BIM?' If the abstract of the paper generally answered each question at a glance, then the paper was selected to review in detail. The authors sought to potentially bridge and pair up the two techniques for a concurrent application. This paper is a foundation to hypothesise and address the potential interactions between OSM and BIM and examine them for practicability. The examination will be followed by structural equation modelling (SEM) and social network analysis.

4.3 Background

4.3.1 Project performance variables.

The need for performance followed by profit margins has caused new technologies to emerge in recent years, though the construction industry has resisted their adoption and slowed steps towards the adoption of alternative techniques. The dynamic and challenging nature of construction projects results in inefficiencies within projects, owing to complicated communication lines, complicated processes, large volumes of detailed data and a lack of practical and effective integration of stockholders (Holt, 2015). The industry requires well-functioning systems to meet the expected level of performance. A system is referred to a set of interactions or interdependent substances that shape a united whole (McNamara, 2006). McNarama (2006) clarified that 'the system has various inputs, which go through certain processes to produce certain outputs, which together, accomplish the overall desired goal' (p. 140). Therefore, to address shortages in housing supply more effectively, builders attempt to find more efficient methods for constructing homes by means of novel materials and innovative construction methods (Mostafa, Dumrak, Chileshe, & Zuo, 2014).

Jha and Iyer (2006) categorised project performance criteria as time, cost, quality, safety and ‘no-dispute’ (see Figure 4.2). The variable of no-dispute is rooted in stockholders’ satisfaction. Gunathilaka, Tuuli and Dainty (2013) added more variables, namely technical performance, planning performance, user satisfaction and productivity/efficiency—they considered these the criteria for project success.

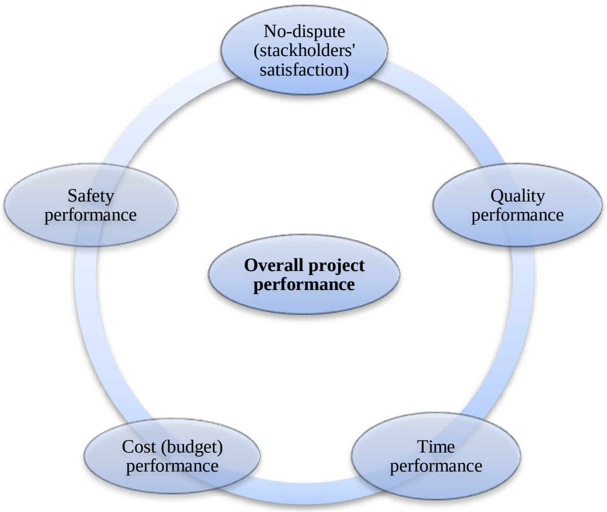

Figure 4.2. The variables of project performance.

4.3.1.1 Budget performance.

Budget (or cost) performance refers to compliance with the estimated budget for a project. It occurs when the total expenses of a completed project do not exceed the estimation. It is a quantitative performance indicator, which is measurable in construction projects (Cho, Hong, & Hyun, 2009).

4.3.1.2 Time performance.

Time performance refers to observing the time baseline in accordance with the initial schedule of projects. This variable is set to avoid project time overrun and extension for project completion. This is a quantitative performance indicator in construction projects (Cho et al., 2009).

4.3.1.3 Quality performance.

Quality performance is achieved when all specifications comply with the required quality standards. Cho et al. (2009) highlighted that quality performance is not measurable, but it is evaluable as a qualitative performance indicator.

4.3.1.4 Safety performance.

This indicator refers to the adherence to reasonable safety considerations to control possible risks to avoid or lower the chances of any incidents or damage (Nevhage & Lindahl, 2008) within an organisation, including construction organisations.

4.3.1.5 Stockholder satisfaction.

Stockholder satisfaction refers to stockholders' expectations regarding receiving a program or product that covers their needs and interests (Susnienė & Vanagas, 2007). To be more specific, stockholder satisfaction refers to compliance with serviceability, in which, every party's expectations of the other project participants are observed. Expectations may be any required, operational contribution that the other parties must make so that the project can progress. Each stockholder plays an effective and contributing role to the results of a project.

Essentially, to meet project performance indicators, new technologies have emerged to simplify process complexity, which could be the root of the issue. Among the new technologies, BIM and OSM have gained considerable reputations. Once the techniques were in practice, various countries reported various degrees of benefits—in such a way as to preclude a general consensus.

Therefore, how the techniques are practised is vital to achieving an acceptable result. As far as OSM is concerned, the possible inconsistencies between manufacturing and construction contractors' activities can exacerbate the inefficiencies in construction sites.

4.3.2 OSM.

Most companies in the construction industry are experiencing a pressing need to enhance their productivity to properly satisfy current demands in the housing sector. Pan and Sidwell (2011) claimed that the increase in demand for housing, in the British context, has caused the industry to consider the use of alternatives to building systems to accomplish the housing projects in an efficient way.

OSM is a modern technique, in which components are constructed off-site and then attached to on-site activities. The off-site components are produced in a controlled manufacturing environment, then transported to, and positioned in, a construction site (Blismas, 2007). OSM has demonstrated the capacity for producing high volume and high-quality residential buildings on the basis of manufacturing principles (Manley, McFallan, & Kajewski, 2009; Li et al., 2014). According to Blismas and Wakefield (2009), OSM can effectively boost the supply of housing. A common, key suggestion in all reports noted above is the need to adopt the 'factory production' style methods in the construction industry, for the purpose of enhancing the efficiency of this sector with manufacturing processes. Additionally, new strategies and targets have been set by the British government and industry sector, which aim to transform the construction industry by 2025, in regards to the achievement of faster delivery, lower costs, lower emissions and improved exports. The house-building sector has attempted to review the operations carried out in this sector and has sought new approaches to improving the ways that new housing projects are delivered. Thuesen and Hvam (2011) stated that the construction industry was experiencing continual pressure to enhance its productivity, decrease costs, enhance quality, improve sustainability and minimise health and safety risks. Such pressures have caused a big dilemma that cannot be resolved without a fundamental change in the delivery of house-building projects. As a result, it is necessary to achieve a deeper understanding of the potentials of applying OSM to the construction industry and also to determine the most significant measures that must be taken to optimise the application of OSM in the house-building sector.

4.3.2.1 Standalone potential capabilities of OSM.

The resistance to change in construction means that researchers must argue the potential benefits of OSM. Ismail et al. (2012) believed that the three most influential factors related to management comprised ‘good collaboration, effective communication channel and team member involvement’ (p.99), and that these factors could play leading roles in the successful adoption of the new techniques in future projects. The adoption of OSM has significantly increased, as OSM has been identified as a technique to reduce the duration of housing projects. This technique has contributed to ambitious improvements in productivity in the Singaporean housing market (Gao, Low, & Nair, 2018). Hamid and Kamar (2012) discussed construction time saving as one achievement of the OSM technique. Hu et al. (2019) found the shorter project duration to be a perceived benefit of OSM. The status of OSM in Malaysia is different. Although the quality of OSM-based housing has been better than that of more traditional housing, some factors such as ‘lack of experience, poor communication, financial problems, and restrictions by stakeholders’ (Hu et al., 2019, p.8) have remained as barriers to the application of OSM. Gao et al. (2018) stated that the lack of a push factor for authorities is a potential barrier to OSM technique implementation in Malaysia. The Chinese government has recognised the optimisations of time, cost and quality through the OSM technique. OSM has been mandated in some jurisdictions and is expected to account for 30% of China’s total construction in the next decade. However, China has been struggling with a lack of regulation and standards to extend the application of OSM (Gan et al., 2018).

The Sustainable Built Environment National Research Centre (SBEnrc) in Australia believes that OSM could offer great opportunities to the construction industry in upcoming decades. It predicted that the demand for affordable housing would double by 2021, compared with 2012. Thus, studies that consider responding to the demand and satisfying time, cost and quality criteria are necessary. SBEnrc also reported that the UK, as a pioneer in fostering and taking advantage of OSM, had a noticeable improvement in its housing program. This means that significant environmental, economic and social benefits have been achieved via OSM (SBEnrc, 2015). Figure 4.3 illustrates the main, potential capabilities of OSM.

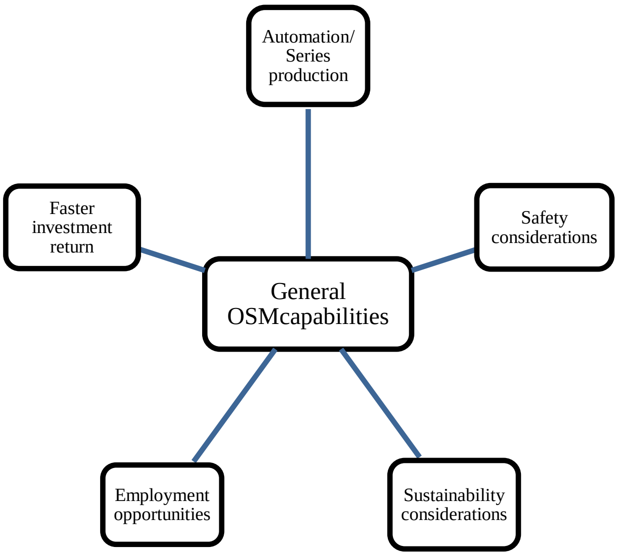

Figure 4.3. General OSM capabilities.

Automation and series production.

The optimisation of time, cost and quality in the construction industry has often been proposed through automation and series production in the factory environment where the construction components are made (Duc, Forsythe, & Orr, 2014). Products are made in a controlled manufacturing environment in such a way that the activities are heavily centralised. Thus, the foundation for the use of automated machinery is indirectly provided on the construction site. Automated, off-site manufacture has been recognised as having more potential revenue through mass customisation (Benros & Duarte, 2009) compared with non-automated OSM. Not only have the aspects of time, cost and quality been observed, but safety satisfaction has also been achieved through automation.

Faster investment return.

Mostafa et al. (2014) believe that ‘The economic-related factors such as consumer price index, changes in the interest and inflation rates are the key driving factors to the demand and supply of houses’(p.64). Dormant capital, trapped investment and longer investment return are the issues that significantly affect the earlier mentioned factors. As OSM can shorten project completion time (Goulding, Pour Rahimian, Arif, & Sharp, 2015), it is predicted that OSM can overcome these kinds of increases in final cost issues. Therefore, the project would be more attractive to the buyers, as the final cost would be competitive. This highlights faster investment return for the investors (SBEnrc, 2015).

Employment opportunities.

It is observed that off-site component production and its business-related activities in the United States fostered the growth of employment opportunities (Eastman & Sacks, 2008), along with other potential benefits. OSM offers steady, long-term job opportunities in factory-based employment, even in remote regions (Arif, Goulding, & Rahimian, 2012; Blismas, 2007).

Sustainability.

The manufactured components of buildings can contribute to the resolution of time, budget and quality inefficiencies. Therefore, there is a belief that OSM bettered sustainability by reducing waste (Duc et al., 2014). OSM, as an end-user value achiever, can be deemed a remarkable contributor to sustainability via satisfying both lean and agile concepts (Mostafa et al., 2014). Mostafa et al. (2014) also highlighted that the key point of the lean technique is waste elimination, while agile focuses on market satisfaction. It is observed that the ultimate price of the final production for end users (those who use the product, e.g. home occupiers) would be more economical than the production in traditional methods (Eastman & Sacks, 2008).

Therefore, proponents of OSM can claim benefits pertaining to factors including social (users' comfort), economic (lower price due to less material consumption and less project overhead costs) and environmental sustainability (less waste-related outcome).

Safety.

Safety improvement is recognised as a continuous challenge in OSM-based projects by optimised construction management. It is highlighted that a tidier construction site results in the betterment of site management (Goulding et al., 2015). In addition, safety measures for working at heights or lifting and loading materials and components are much more controllable and applicable in a factory environment. Thus, better working conditions are provided in factories—resulting in improvements to health and safety (Nahmens & Ikuma, 2011).

A suitable level of OSM application not only expedites a project as a catalyst but also makes it economical. An early decision toward OSM-related activities and an efficient process would eliminate inefficiencies and avoid any disturbance in the project

(Gibb, 2001). The uptake level can vary in the project, based on the characteristics and situation of the project.

4.3.3 BIM.

One of the countries that pioneered rethinking construction is the UK. The authorities, engineers and researchers in the UK found BIM capable of solving problems of low productivity and costs overrun in the construction sector (Jonsson & Rudberg, 2014). BIM is the process of developing and applying a simulated model of planning, designing, construction and operation of a building. The model contains a collection of digital data and rich information about all details related to a project, during its life cycle. The BIM model originated from a smart 3-dimensional CAD which is automatically adaptable to any change and is connected to a shareable database, which performs as a common source among parties involved in a project. As there are different levels of details for a BIM model, sometimes it might be designed for a building only for visualisation and analysis of safety cases or for the maintenance of the project (Jung & Joo, 2011). BIM entered the area of architecture, engineering and management with different levels of uptake (Kim, Park, & Chin, 2016). The level of BIM uptake is determined by the activities for which BIM is supposed to be used for. This theme determines the level of practices, integration and the professional level of the companies in BIM application in different countries. Thus, the uptake level varies from one company to another (Haron, Marshall-Ponting, & Aouad, 2010; Newton & Chileshe, 2012). Chong, Lopez, Wang, Wang and Zhao (2016) conducted a case study claiming that the cultural and managerial aspects allow for a progressive BIM adoption in Australia and China. Almost seven dimensions of BIM can be considered, from visualisation to facility management for this adoption (Kim et al., 2016).

4.3.3.1 Standalone capabilities of BIM.

It can be stated that a BIM full package contains various tools—each tool with its own practicability in different schemes within a project. A BIM package can be imagined as a general tool kit containing different tools. A wrench, as a tool in a BIM package, can tighten a nut. Structural components need to be attached to one to erect the steel structure (steel skeleton) of a building. In this regard, the wrench can tighten the nuts to keep the stability of the structure, which refers to the technical performance of the structure. As reflected in research by Chong, Lee and Wang (2017), Olatunji (2012) and Beveridge (2012), Figure 4.4 presents eight categories as the main BIM capabilities, which are applicable at different levels of BIM uptake in the project life cycle.

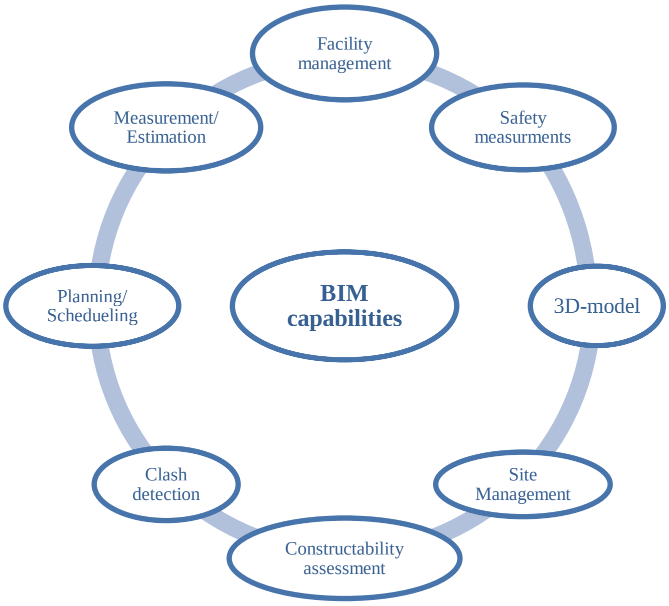

Figure 4.4. Main BIM capabilities/practices.

This unique collection of the constructive capabilities gives BIM the potential for adoption not only in building but also in infrastructure projects (Chong et al., 2016). These capabilities even have the potential to lead an efficient and effective contract administration (Chong, Zin, & Chong, 2012). Chong et al. (2012) prototyped an electronic dispute resolution (e-DR) that optimises contract administration. They based the prototype on a guideline containing all the data of agreements between the experts involved in a project.

4.3.3.2 3-D modelling.

This capability offers a general volumetric shape of the elements in structural, architectural and instalments (mechanical and electrical) designs. The perspective of 2-D drawings is visualised via 3-D modelling. In this model, the completed form of a building can be observed by the construction team members and the client(s) in a 3-D environment and they can have a virtual walkthrough before completion of the building. It visually represents what the building will look like from both external and internal perspectives (Clevenger, Ozbek, Glick, & Porter, 2010). This is one of the most basic applications of BIM.

4.3.3.3 Measurement and estimation.

The BIM model makes estimations about project costs on the basis of the structural components presented in the model. Most of the time, this part is referred to as a ‘5-D’ option. Quantities are inferred from the model and considered in estimations. When a new specification is added to the model, the estimation status is accordingly updated. The client can simply determine and approve the cost of changes occurred to the primary design (Aibinu & Venkatesh, 2014). Therefore, offering the quantity of materials with high accuracy and predicting their total cost is possible with a BIM model.

4.3.3.4 Planning and scheduling.

BIM planning is the ability to develop a digital work breakdown structure (WBS) which prioritises activities and links them to each other. It can be stated that sequencing capability lies in planning, while scheduling capability refers to assigning a duration to the activities (Büchmann-Slorup & Andersson, 2010). Scheduling is a tool to add the digital model to the time factor. BIM puts all components of the construction within a certain timeframe, outlined by the schedule; it allows users to check the project path towards the end point in an organised manner (König, Koch, Habenicht, & Spieckermann, 2012).

These capabilities can be followed by the capability of monitoring a project's progress, along with the possibility of rescheduling activities.

4.3.3.5 Clash detection.

As a building project comprises numerous components in structural, architectural, mechanical and electrical designs, the chance of design interference while the drawings are being interpreted is high. BIM offers chances to detect conflict by combining the 3-D models of the designs, which is a remarkable capability. In addition, in case of huge projects, there may appear thousands of situations in need of change, which finally lead to this type of clash. Contractors claim that they are able now to remove almost all of them (Beveridge, 2012). This is recognised as a widely used application of BIM, which is described as low-hanging fruit (Seo, Lee, Kim, & Kim, 2012).

4.3.3.6 Constructability.

Almost all projects involve a stage for creative thinking, during which lots of ideas are proposed, but not all of them can be accepted. BIM has the capacity to make this process easier, by simulating the ideas in a way to simply decide if they are practical and affordable, or not (Tauriainen et al., 2014). Further, A BIM model can be updated based on every change in the model. This means that the components automatically adjust themselves to the new state of the model (Farnsworth, Beveridge, Miller, & Christofferson, 2015). Thus, the assessment of any variation in the outcome is possible, as BIM is a smart model which reflects constructability.

4.3.3.7 Site coordination.

Sequence clarification, via a BIM model, gives site coordinators more chances to recognise the required trades, materials and equipment to prepare the commencement and execute every construction activity better. Overall, a coordinating office can be established, where employees can review the model whenever needed, at a specified place. It can be used in design meetings, in case the whole model or some clashes need to be reviewed, as well as during the decision-making process (Paranandi, 2015).This point reflects the ability of site coordination.

4.3.3.8 Safety measurements.

Safety measurements refer to BIM’s capabilities for automated safety measurement, alerting fall situation from heights and highlighting the best access to the routs for plant operation—and specifically, offering optimum lifting drawings for crane operation (Zhang, AlBahnassi, & Hammad, 2010).

4.3.3.9 Facility management.

Facility management refers to the ability to manage the operation of building, in case there is a need to extract the data of the existing building. A digital BIM model can be deemed as a foundation for perfect facility management. As an example, knowing about the in-built components is possible if the removal of a part of a building is required (Nicał & Wodyński, 2016). The laser scanning ability in BIM can collect numerous and accurate spatial data of construction progress and store the information that might be required in any maintenance or renovation situations (Beveridge, 2012). This ability is vital to conducting the facility effectively and efficiently over its entire life (Arayici, Onyenobi, & Egbu, 2012).

4.3.4 Barriers for the development of the hybrid OSM–BIM system.

4.3.4.1 Barriers on the BIM side.

The nominated elements of BIM in Section 4.1, which have been brought from industry and academia, reflect the constructive applicability of BIM. Although many influential BIM tools offering the elements have been introduced, the tools alone have not been sufficient for efficiently implementing BIM. A range of changes are required, in terms of 'work practices, staff skills, relation among BIM implementation team, and contractual arrangement' (Migilinskas, Popov, Juocevicius, & Ustinovichius, 2013). Because there is no willingness to adopt BIM beyond mandatory themes (akin to the UK's level 2 BIM uptake), it has officially only been partially adopted (Migilinskas et al., 2013).

4.3.4.2 Barriers on OSM side.

The most common barriers to OSM have been reported to be longer project durations and the excessive costs of modifications. The relevant excessive costs in OSM-based projects (costs which are not applicable to non-OSM projects) are assumed to be the most debatable issues for OSM uptake (Blismas & Wakefield, 2009).

Blismas, Pasquire and Gibb (2006) categorised material, labour and transportation costs as the most direct and costly exercises, while site facilities, crane use and rectification of works were taken into account as indirect costs. The costly items, together with consistent management and safety measures, are the determining factors of OSM uptake. The literature review determined that the barriers of OSM projects are fragmentation among participants, high initial capital cost, reluctance of insurers and financial providers, excessive cost compared with non-OSM projects and insufficient accurate drawings. Every single barrier negatively affects projects and potentially hinders the practicability of the techniques. Therefore, as an attempt to remove the barriers on both sides (BIM and OSM), it is reasonable to consider the development of a hybrid OSM–BIM system.

4.4 Discussion

The current study suggests the development of an OSM–BIM system. The potential supplementary and overlapping capabilities, as the potential OSM–BIM interactions (POBIs), to enhance project performance has been observed and highlighted. The great capabilities of the two newly emerged techniques make them worthwhile to use. However, as discussed in section 3.6, professionals argue about the applicability of their attributes and capabilities. BIM has been said to possess some potential to reinforce OSM. It has been claimed that suitable levels of BIM uptake are capable of resolving the barriers reported in OSM projects, to meet project performance.

Based on the literature provided in the current study, BIM can step in and rectify the potential barriers encountered in OSM-based projects. Regarding the fragmentation of participants (designer, manufacture and construction contractors), the nature of BIM's information-sharing platform links the participants. The construction industry will take a determinant step toward project performance once the inefficiencies caused by the fragmentation issue are removed. BIM can offer the exact specifications to keep the required quality when producing components, which is an important consideration from a manufacturer's perspective. BIM can also address how to merge components to meet the expected functionality, within the delivery and operation stages. Therefore, there would not be any chance of hidden functionality failures. What this means is that the assurance of a reasonable construction delivery encourages the stockholders and the investors. Further, a perfect feasibility assessment is possible through a systematic, smart and digital environment of a project. This assessment can be followed by the accuracy in planning and scheduling, clash detection, measurement and estimation—

contributing to project performance. This range of offers through BIM trims any excessive costs and optimises the budget assigned to an OSM project. As a result, a better initial capital cost may be concluded, which encourages the finance provider.

The current study hypothesised and predicted some constructive interoperability as interactions between the two techniques. Therefore, this article conceptualised the claims with the purpose of examining them through an empirical study in the future.

The potential interactions are flagged in Figure 4.5. The figure shows that the two techniques can tackle barriers and bridge the potential capabilities to achieve a range of interactions that optimise project performance. The question is how to conceptualise the interactions. It is also shown that the interactions need to be systematically applied to fully benefit the projects. Their systematic adoption could be achieved through questioning how, where and when to implement them, and where the inbounding points of applying the interactions are within an OSM–BIM-based project. Therefore, the systematic adoption presented in Figure 4.5 refers to a system through which all the detected, nominated interactions can be effectively applied in the design and construction stages.

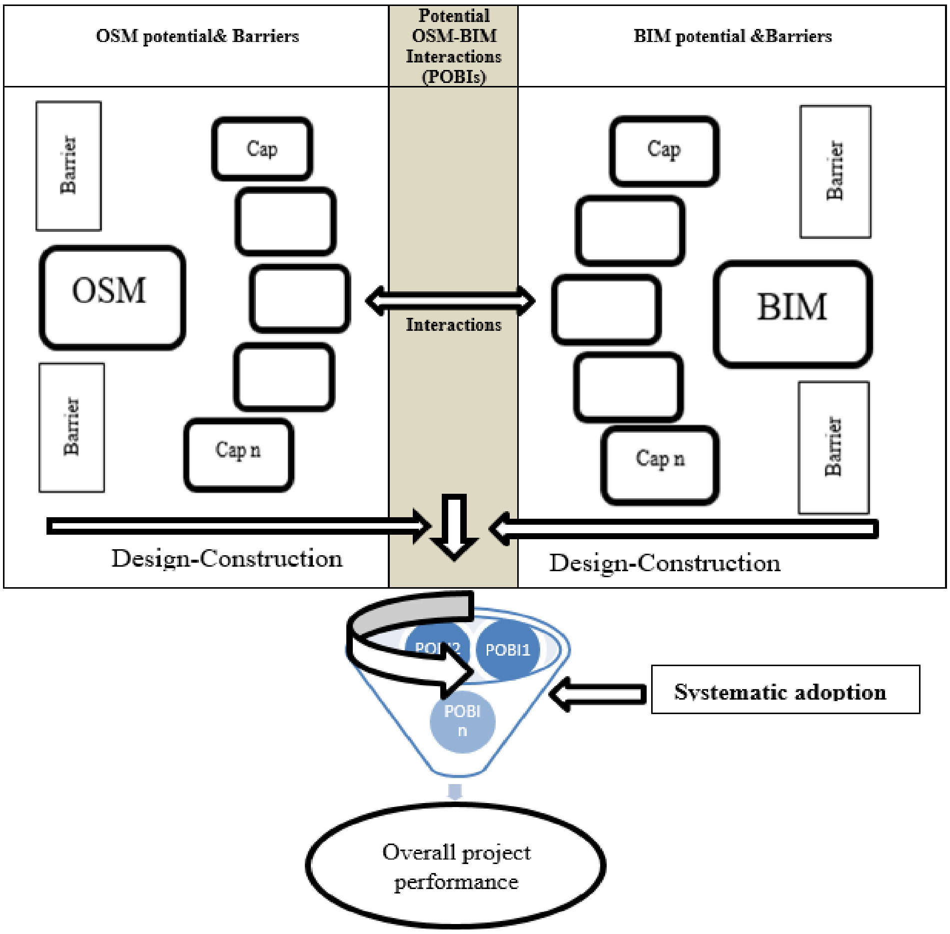

Figure 4.5. A conceptual framework to develop a hybrid OSM–BIM system for project performance.

4.5 Conclusion and Further Research

The scope of this study lies in the fields of BIM, OSM and project performance. This study conceptualised a framework for a new hybrid OSM–BIM system to enhance project performance. Through the literature review, the capabilities of BIM and OSM (See Figures 4.3 and 4.4) and their direct and indirect effects on performance were discussed, respectively. In addition, the arguments about barriers of each technique were briefly pointed out in section 3. 3. 4. The potential constructive interactions were conceived by analysing and evaluating the capabilities and attributes of the techniques in the consideration of performance. Figure 4.5 suggests that the two techniques are capable of going beyond the barriers and moving towards a range of potential OSM–

BIM interactions (POBIs) at the design and construction stages. The design stages refer to considerations corresponding to the design for manufacture assembly and construction delivery (the construction site activities). As reflected in Figure 4.5, the interactions are assumed to be more effective under a systematic adoption. The systematic adoption can be defined as a system through which the interactions would be correctly applied at the right time and stages under a collaborative involvement of the participants. This study is a foundation toward detecting the potential technical interactions, which needs to be followed by systematic adoption, applicable in planning and managerial schemes.

Chapter 5: Potential Interactions Between Building Information Modelling and Off-Site Manufacturing for Productivity Improvement

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Abstract

Purpose- New methods have been introduced as revolutionary approaches in the construction industry, such as off-site manufacturing (OSM) and Building Information Modelling (BIM). Although these approaches can provide many benefits, there are still barriers to meeting the expectations of improved construction productivity via their implementation. Hence, this paper aims to critically review the capabilities of OSM and BIM techniques, as well as their potential interactions, in productivity improvement.

Design/methodology/approach- A scoping review approach was adopted, where 100 peer-reviewed journal articles were collected to analyse the capabilities of OSM and BIM, as well as their potential interactions, in productivity improvement as assessed by key productivity indicators (KPrIs).

Findings- The results reveal seven BIM-based capabilities and six OSM-based capabilities, as well as 12 potential OSM–BIM interactions that have significant potential for satisfying KPrIs.

Originality/value- An integrated framework has also been developed to clarify and conceptualise the roles of OSM–BIM interactions in their designated KPrIs. The research has developed insightful and practical references for strategic planning and management in OSM–BIM-based projects.

Keywords Construction, Project Performance, Productivity, Capabilities, Integrated Framework, Interactions, OSM, BIM

5.1 Introduction

Construction professionals have always searched for new methods to improve productivity. However, the selection of the most suitable and practical construction method remains a common challenge in construction performance (Ferrada & Serpell, 2013). Traditionally, researchers have attempted to target productivity improvement through benchmarking the best practices with productivity indicators in construction projects (Arditi & Mochtar, 2000; Cox, Issa, & Ahrens, 2003; Enshassi, Kochendoerfer, & Abed, 2013). Achieving success in the establishment of new techniques to acquire modernised technologies very much depends on the balance of the integration of the capabilities and potentials of the system against the fragmentation of the processes and parties involved in a project (Blayse & Manley, 2004). The collaboration of all parties is key to performance enhancement and successful project delivery (Walker, 2018).

Building Information Modelling (BIM) is a new technique that has recently arisen in the construction industry worldwide, and operates at different stages of the life cycle of a project. BIM, through its visualisation and information-sharing abilities, enables stakeholders to combine designs and assess the outcomes during the early stages of a project (Ding, Zuo, Wu, & Wang, 2015). Porwal and Hewage (2013) observed in their case study that BIM has been proven to improve the construction process through efficient coordination among the stakeholders and the provision of accurate information. In fact, many countries have actively promoted BIM technology. The US is believed to be one of the pioneering countries in the adoption of BIM, where the public sector and departments at different levels have established BIM programmes, roadmaps and standards (Cheng & Lu, 2015). The United Kingdom (UK) government has the same approach to BIM and has even regulated the mandatory measure to use of BIM Level 2 on certain projects (Khosrowshahi & Arayici, 2012; Ganah & John, 2014).

The mandatory use of BIM could bring increased competitiveness and productivity in the long run (Bryde et al., 2013). The potential of BIM to increase construction productivity and performance in the broader sense has been extended from buildings to infrastructure projects (Chong et al., 2016). The clarification of responsibilities, agreements and duties through BIM effectively contributes to project productivity (Azhar, 2011; Chong et al., 2017; Love, et al., 2011). Nevertheless, BIM is still evolving and its potential very much depends on certain factors, such as project size, team members' proficiency, the communication conditions among the project's members and external organisation-related factors (Barlish and Sollivan, 2012).

Off-Site Manufacturing (OSM) is a method in which components are produced via factory activities and then assembled and erected via on-site activities (Khalfan & Maqsood, 2014). OSM has been defined as a technique for improving both quality and quantity in construction. OSM consistently demonstrates higher productivity improvement compared with traditional construction based on on-site activities only (Eastman & Sacks, 2008). It has also been introduced as the most influential agent in creating noticeable opportunities to improve the construction industry globally in future decades (SBEnrc, 2017).

In response to stakeholders and end users' expectations, the interactions between these new technologies have put on the agenda to optimise time, cost and quality, as the main aspects determining construction performance (Aliakbarlou et al., 2018). Although these new concepts can be applied to projects independently, some characteristics of each concept will cover the others via hybrid concepts to improve the stages of the project. For example, BIM is able to supplement certain other new technologies in achieving their objectives. BIM and lean collaboration has been a widely highlighted outcome, owing to the integration of these concepts. Fifty-six interactions have been identified between BIM and lean collaboration that improve the construction industry (Sacks et al., 2010). Another research study linked these two techniques under a mutual mission of waste reduction and efficiency growth, which generally created value in the construction sector (Bi and Jia, 2016). It has been observed that an enriched model developed from BIM standards not only creates a platform for exact data exchange, through an effective communication line promoting lean concepts (Hamdi and Leite, 2012; Sacks et al., 2009), but also improves prefabrication systems (Moghadam et al., 2012; Nawari, 2012). BIM is perceived to be one of the new technologies capable of accompanying OSM. BIM specifications seem to confer the ability to support and complement OSM and fulfil its potential once applied in practice.

Therefore, this paper aims to critically review the capabilities of both the OSM and BIM techniques, as well as their potential interactions in productivity improvement. A scoping review was adopted and the pathway was developed based on the question, ‘which productivity indicators have the capacity to be affected to optimise project progress?’, followed by another question: ‘which indicators could be affected via the interaction of these two concepts and how do these capabilities overlap or work individually?’ For this purpose, initially key productivity indicators (KPrIs) need to be developed through the literature review before investigating the effects of BIM and OSM on these indicators. This paper summarises how BIM can contribute to the improvement of project progress in an OSM-based project and vice versa. More specifically, the capabilities of BIM include highly accurate information regarding the specifications of components, visualisation of the project and site via a 3D model, a rapid information-sharing platform for early decision-making and optimum planning/scheduling, all of which can promote productivity in OSM-based construction projects.

5.2 Literature Review

Low productivity on construction sites has always been one of the stakeholders' main challenges in the construction industry. Many researchers have tried to develop various ideas to identify effective practices from different concepts and integrate these to promote the industry's status. The focus has been on improving customer satisfaction through product and process development, which required fostering of commitment between all parties involved in a project (Murray, 2003; Segerstedt and Olofsson, 2010). As such, KPrIs play a significant role in a construction project.

5.2.1 KPrIs in construction.

Productivity variables in construction projects can be referred to as the variables by which the actual project progresses as the output will occur and be assessed by comparing it to the planning and scheduling template. Dozzi and AbouRizk (1993) stated that 'traditionally productivity has been defined as the ratio of input/output' (p. 1). Input refers to materials ($), personnel (P-H), management and equipment ($), while output refers to the production unit. The high costs of construction projects are in the nature of these projects. Thus, the minimum input expected to obtain the maximum output is deemed 'productivity achievement' (Huang et al, 2009). In this paper, the authors attempted to clarify the terms construction 'performance' and 'productivity'. The authors refer to the performance perspective as a broad overview, which can be followed by the productivity perspective in a narrow sense. This means that productivity is aligned with performance. Therefore, the productivity perspective may follow the performance perspective. However, Dozzi and AbouRizk (1993) believe that the term 'performance' can also be used instead of 'productivity'. Comin (2006) stated that 'Total Factor Productivity is the portion of output not explained by the number of inputs used in production' (p. 260). Thus, the production unit can be deemed as project progress in construction projects.

There is a wide range of indicators impacting productivity that can be designated under the socio-economic conditions present in both developing and developed countries (Hasan et al., 2018). These indicators have been categorised into quantitative and qualitative indicators; quantitative indicators are those that are physically measurable and applicable by means of numbers, amounts and units, such as a report of costs, completion percentage, the amount of materials and the number of human resources, while qualitative performance indicators are those that are not easily and tangibly measurable for example, the status of safety (Cox et al., 2003) or the functionality of management (Botje et al., 2016). These indicators do not offer accurate data on a project's status, but describe a situation, such as a safety report (Cox et al., 2003). The conceptual framework below (Figure 5.1) summarises the papers showing the categories and subcategories of productivity indicators in construction projects (Allmon et al., 2000; Arditi and Mochtar, 2000; Bassioni et al., 2004; Chan et al., 2004; Chan and Kumaraswamy, 1995; Chan, 2009; Cox et al., 2003; Diamantopoulos and Winklhofer, 2001; Dozzi and AbouRizk, 1993; Enshassi et al., 2013; Kapelko et al., 2015; Meng, 2012; Poirier et al., 2015; Takim and Akintoye, 2002).

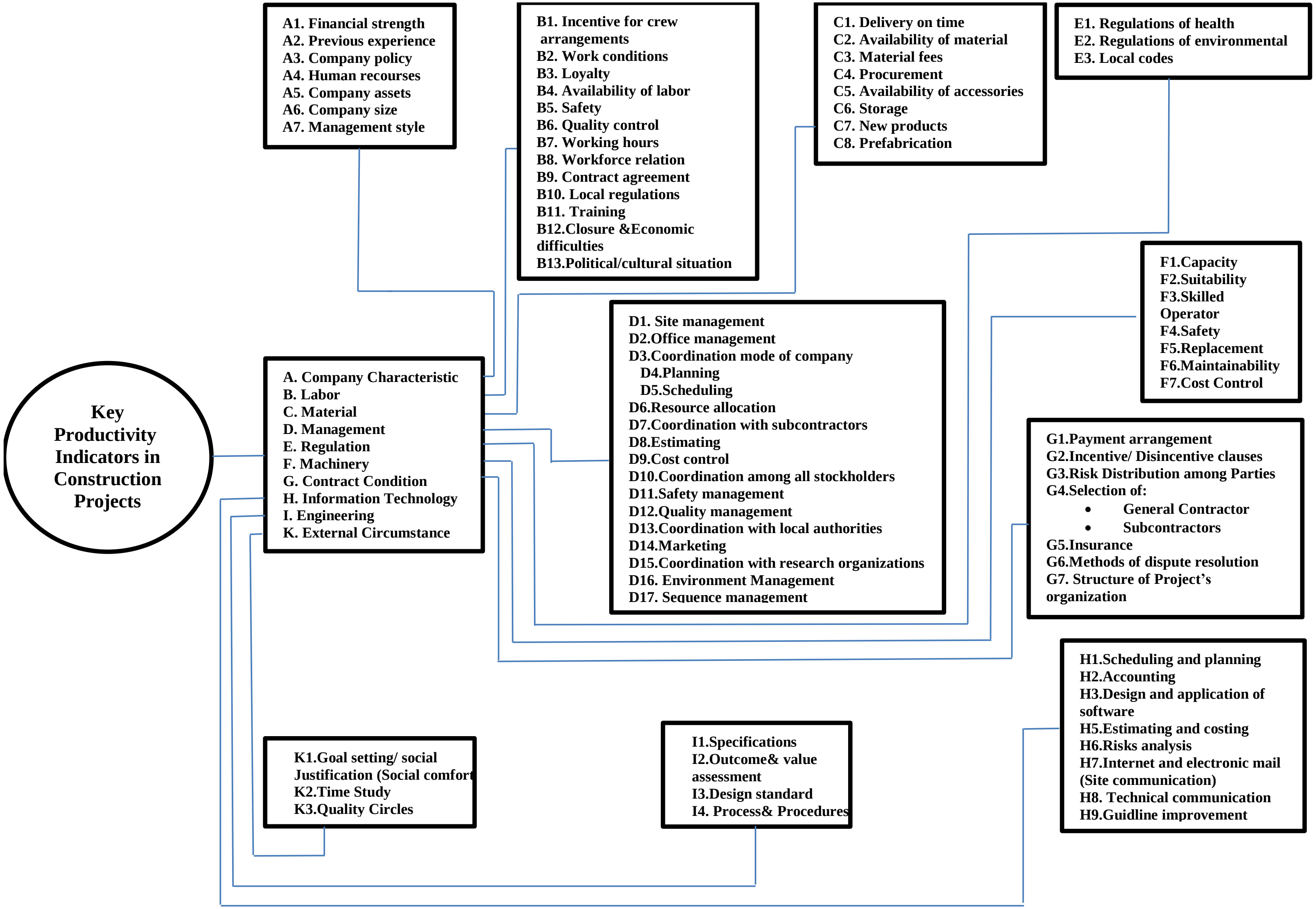


Figure 5.1. Conceptual framework of key productivity indicators leveraging product success.

5.2.2 BIM and the level of adoption.

BIM is the process of developing and applying a simulated model of the planning, designing, construction and operation of a building, which contains a collection of data and rich information on all the details relating to a project during its life cycle. BIM is a smart 3D CAD, automatically adaptable to any change and connected to a database that acts as a common source for all parties involved in the project.

BIM has moved into the areas of architecture, engineering and management. The level of BIM uptake is determined by the activities for which it was designed to be used. This determines the level of integration of practice and professionalism in a company using BIM. Thus, the uptake level varies from one company to another (Haron et al., 2010; Newton and Chileshe, 2012). Figure 5.2 presents the practices derived from BIM. Chong et al. (2014) referred these practices to the common capabilities include sequencing, clash detection, facility management, constructability assessment, estimation and measurement (Chong et al., 2014). The improvement of conflict management has been noted as a capability of BIM, as potential disputes can be better controlled (Charehzehi et al., 2017).

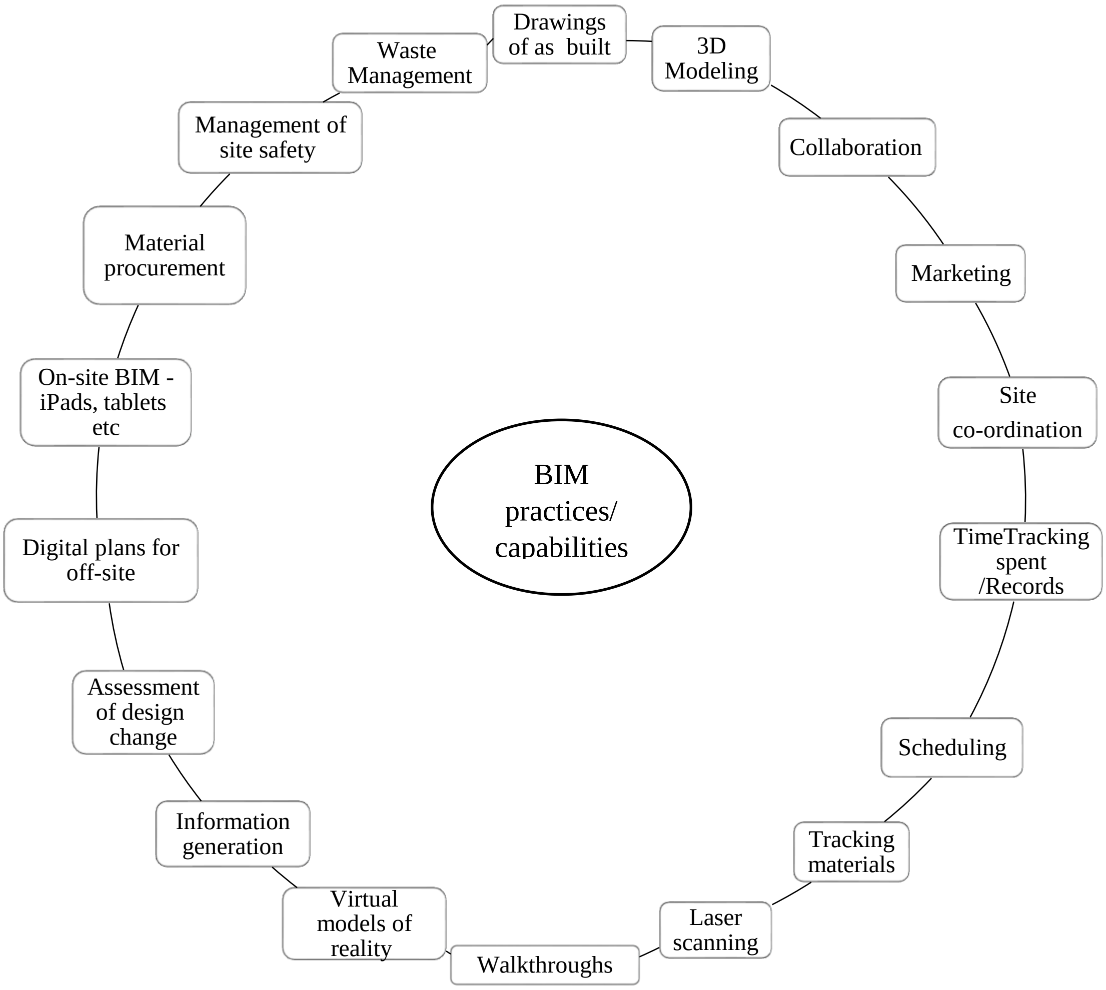


Figure 5.2. The potential practices of BIM in construction projects.

5.2.3 OSM and the level of adoption.

The OSM approach is a modern technique in which prefabricated construction components are merged and erected as an on-site activity. The components are produced off-site in a controlled manufacturing environment and then transported to and positioned on the construction site (Blismas, 2007). The severe lack of construction workers and material resources after the world wars of 1914–1918 and 1939–1945 opened the gate for the advent of OSM. Many terms have been considered for this concept (Vernikos et al., 2014), all of which, with a few variations in their applicability, have resulted in the OSM system that is now commonly used (Amanda et al., 2017).

An industry report prepared by Sustainable Built Environment National Research Centre (SBEnrc, 2017) declared the UK to be a pioneer in fostering and benefiting from OSM, which had resulted in a noticeable improvement in their construction programme, meaning that significant environmental, economic and social benefits have been achieved via OSM. The market in the Asia-Pacific, as the most demanding market for investment in OSM, has been calculated to amount to USD100 billion up until 2020. A report in 2012 showed that China had the largest market share (60%), while the smallest market share belonged to Indonesia, at just 5%. Japan and Australia shared 22% and 7% of this investment, respectively. It has been noted that the rate of growth of the OSM market in Australia will dramatically increase due to the high costs of both labour and importing manufactured components. Strengthening the internal market and fostering job opportunities in Australia may thus be another main reason for harnessing the OSM approach. Some obvious values arising from OSM are 'reduced risk of delay, reduced likelihood of variation, increased construction safety, more attraction to home buyers, greater return on equity, reduced material cost, less theft, vandalism, and damage of material' (SBEnrc, 2017, p.8-9). The costs of OSM-based projects that are not applicable to non-OSM projects have been arguably assumed to be a barrier to the uptake of the OSM approach (Blismas & Wakefield, 2009). Certain extra costs have been seen to place pressure on projects due to the lack of systematic uptake, highlighting which stage and how the uptake of OSM should be considered. The uptake level may vary in between projects based on the characteristics and situation of the project (Blismas & Wakefield, 2009). Although many researchers have identified significant benefits from the utilisation of OSM, there are still barriers to embracing the

OSM approach and reaping these benefits in Australia (Wynn et al., 2013). Every action is crucial to support the decision regarding OSM uptake via offering supplementary abilities to promote productivity and efficiency (Blismas & Wakefield, 2009).

5.2.4 The concept of interactions.

A combination of techniques may sometimes increase the capabilities of both techniques. One proposed solution to the problem of cost overrun in the construction industry is the concomitant application of lean and linear programming strategies as an interacting measure (Gade, 2016). BIM, as an interactive technique, has been used to influence the industry by providing a collaborative approach and an information-sharing platform. For instance, the concepts of lean principles interact with BIM in both positive and negative ways (Sacks et al., 2010). An enriched BIM model can effectively support OSM projects at different uptake levels, subject to capturing suitable readable data available in a BIM model and exchanging these with other stakeholders (Nawari, 2012). Wynn et al. (2013) believe that construction efficiency can be promoted by an OSM-oriented process that is supported by IT solutions such as BIM and Acconex.

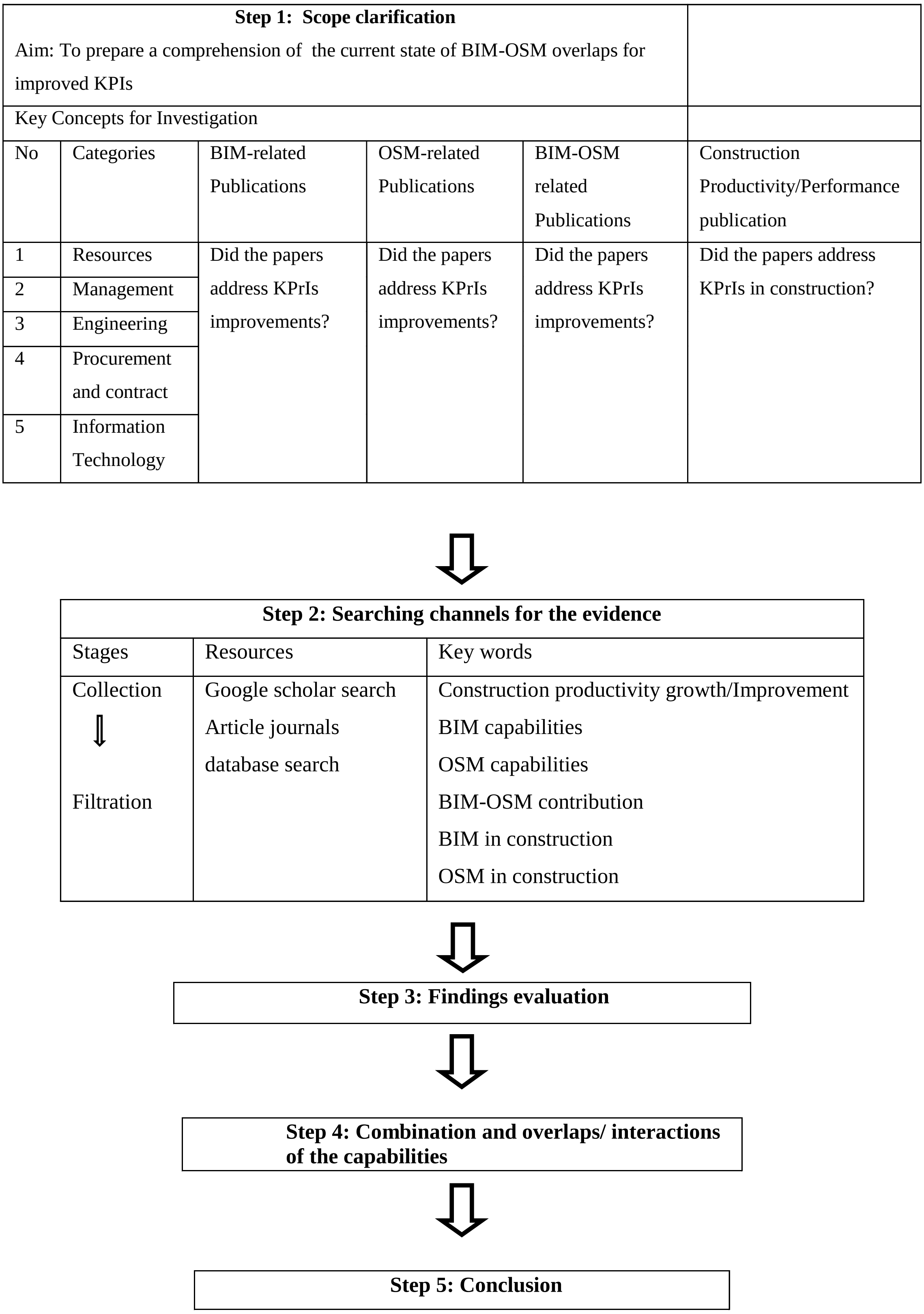
5.2.4.1 BIM in OSM.

OSM, as an advanced technique, holds tremendous potential to interact with BIM to contribute to improvements in the construction industry (Goulding et al., 2012). Faster progress, quality and cost optimisation and minimisation of work corrections on site; or in the broader sense, a more sustainable site, arise from the integration of off-site produced units in a construction project (Arif et al., 2012; Khalfan and Maqsood, 2014). Previous studies, however limited, have briefly discussed the potential benefits of BIM in OSM. For example, BIM has been recognised as having the potential to link design, manufacturing and construction through a workshop in relation to OSM (Goulding et al., 2012). Vernikos et al. (2013, p. 152) interviewed 12 leading BIM experts and innovation directors and found that BIM can improve OSM through ‘configuration and interface management; information data flow; project management and delivery; procurement and contracts’. Nawari et al. (2012) stated that an enriched BIM model can be effectively used by not only manufacturers to produce prefabricated components, but also by users needing to capture all related data from the BIM model, which will improve building processes in OSM-based projects. Ezacn et al., (2013) explained that how BIM can cover some of the weaknesses of OSM that have been reported in the literature. Amanda et al. (2017) revealed far greater benefits of BIM in OSM than in traditional construction techniques by considering a range of parameters, such as time, cost, quality, sustainability, market culture, poor integration and safety, among others.

The current research proposes an interaction between OSM and BIM through an integrated framework for productivity improvement. As an example, precise information on the details of a component, including its dimensions and assembly descriptions, visible via BIM can assist fabricators to better position the component. to exploit this capability, some researchers believe that design data are effectively transferable into the prefabrication process in a factory environment via BIM’s capacity to offer exact digital specifications, although others have stated that despite the BIM specifications, the success of new concepts depends on organisational strategy (Vernikos et al., 2014) and project governance functions (Hjelmbrekke et al., 2017).

5.3 Review Approach

The approach taken for the scoping review was to retrieve the necessary data from the literature. This review approach consolidates the evidence on the research variables on the basis of their potential links or synergies (Pham et al., 2014). This is particularly useful for new topics and dealing with a lack of comprehensive literature (Peters et al., 2015). Figure 5.3 shows the overall processes, along with the main contents, that shaped the scoping approach. Through the literature review, six categories were identified for improving construction productivity either individually or synergistically: resources, management, engineering, procurement and contracts, information technology and sustainability. The second stage involved searching the channels of evidence, including the collection and filtration of the type of literature. Relevant papers were identified by keyword searches of Google Scholar and library databases, and their relevance was assessed by examining their abstracts was. The keywords used in the searches were construction productivity growth/Improvement, BIM capabilities, OSM capabilities, BIM in construction, OSM in construction and BIM–OSM contribution. Figure 5.3 shows the selection process. In detail, the first step of the selection process retrieved articles relating to performance and productivity in construction. Thirty-four papers were identified, and following assessment, 27 were retained based on the required productivity indicators. Next, these papers were scanned to identify a clear understanding of the definition of BIM and OSM and their capabilities. Twenty OSM-related papers and 57 BIM-related papers were screened, with 16 and 50 retained, respectively. The identification process was followed by an in-depth search on the current state of BIM–OSM interactions, from which seven relevant papers were retrieved and analysed. The screening process was necessary to obtain and analyse reliable and accurate sources of materials for the literature review. The research questions were then developed, asking how BIM, OSM and BIM–OSM overlaps and interactions may improve KPrIs. Finally, 100 journal articles covering the scope of these techniques were selected.



Step 1: Scope clarification Aim: To prepare a comprehension of the current state of BIM-OSM overlaps for improved KPIs					
Key Concepts for Investigation					
No	Categories	BIM-related Publications	OSM-related Publications	BIM-OSM related Publications	Construction Productivity/Performance publication
1	Resources	Did the papers address KPrIs improvements?	Did the papers address KPrIs improvements?	Did the papers address KPrIs improvements?	Did the papers address KPrIs in construction?
2	Management				
3	Engineering				
4	Procurement and contract				
5	Information Technology				

⇩

Step 2: Searching channels for the evidence		
Stages	Resources	Key words
Collection ⇩ Filtration	Google scholar search Article journals database search	Construction productivity growth/Improvement BIM capabilities OSM capabilities BIM-OSM contribution BIM in construction OSM in construction

⇩

Step 3: Findings evaluation

⇩

Step 4: Combination and overlaps/ interactions of the capabilities

⇩

Step 5: Conclusion

Figure 5.3. The selection process for the literature review.

5.4 Data Analysis and Findings

Table 5.1a shows the four research categories investigated in detail; namely, construction productivity/performance, BIM in construction, OSM in construction and BIM–OSM interaction. Productivity/performance growth and the indicators used in construction projects were discussed from the first category of papers identified. The role of BIM and OSM and their capabilities as standalone improvement approaches were described from the second and the third categories, while the interactions between BIM and OSM were investigated in the last category of papers. Table 5.1b summarises the number of articles reviewed in each of the research areas.

Table 5.1a *Peer-reviewed publications in the proposed research areas*

No	Academic researches	Construction performance/ Productivity publications	BIM in construction publications	OSM in construction publications	BIM–OSM Interaction confirming publications
1	Amanda et al. (2017)				X
2	Ahmad and Thanheem (2018)		X		
3	Aliakbarlou (2018)				
4	Allmon et al. (2000)	X			
5	Arashpour et al. (2015)			X	
6	Arditi and Mochtar (2000)	X			
7	Arif et al. (2012)	X			
8	Azhar (2011)		X		
9	Azhar (2012)		X		
10	Azhar (2009)		X		
11	Bank et al. (2010)		X		
12	Barati et al. (2013)		X		
13	Barlish and Sullivan (2012)		X		
14	Bassioni et al. (2004)	X			
15	Bi and Jia (2016)		X		
16	Blayse (2004)	X			

No	Academic researches	Construction performance/ Productivity publications	BIM in construction publications	OSM in construction publications	BIM–OSM Interaction confirming publications
17	Blismas (2007)			X	
18	Blismas et al. (2006)			X	
19	Blismas and Wakefield (2009)			X	
20	Blismas et al. (2005)		X		
21	Bryde et al. (2013)			X	
22	Boyd (2012)			X	
23	Chan et al. (2004)	X			
24	Chan and Kumaraswamy (1995)	X			
25	Chan (2009)	X			
26	Charehzehi et al. (2017)		X		
27	Cheng and Lu (2015)			X	
28	Chen and Lu(2014)		X		
29	Chong et al. (2017)		X		
30	Chong et al. (2014)		X		
31	Chong et al. (2016)				
32	Cirbini et al. (2015)		X		
33	Cox et al. (2003)	X			
34	Diamantopoulos and Winklhofer (2001)	X			
35	Ding et al. (2014)		X		
36	Ding et al. (2015)		X		
37	Dozzi (1993)	X			
38	Eastman and Sacks (2008)	X			
39	Murry (2003)	X			
40	Elnaas and Philip (2014)	X			
41	Enshassi et al. (2013)	X			
42	Ezcan et al. (2013)				X
43	Ferrada and Serpell (2013)	X			
44	Forgues et al. (2012)		X		
45	Gade (2016)	X			
46	Ganah and John (2014)			X	

No	Academic researches	Construction performance/ Productivity publications	BIM in construction publications	OSM in construction publications	BIM–OSM Interaction confirming publications
47	Ghazali, W., & Irsyad, W. A. (2016)		X		
48	Goulding et al. (2012)				X
49	Goulding et al. (2015)			X	
50	Hamidi (2012)				
51	Haron et al. (2010)		X		
52	Hasan et al. (2018)	X			
53	Hergunsell et al. (2011)	X			
54	Haung (2009)	X			
55	Hjelmbrekke et al. (2017)				
56	Irizarry et al. (2013)		X		
57	Kang et al. (2007)		X		
58	Kapelko et al. (2015)	X			
59	Khalfan and Maqsood (2014)			X	
60	Khoshnava et al. (2012)				
61	Khosrowshani and Arayici (2012)			X	
62	Lee et al. (2015)		X		
63	Lessing et al. (2005)				
64	Li et al. (2014)		X		
65	Love et al. (2011)		X		
66	Lu and Korman (2010)				X
67	Lu et al. (2017)		X		
68	Meiling et al. (2012)			X	
69	Meng (2012)	X			
70	Moghadam (2012)		X		
71	Nawari (2012)				X
72	Newton and Chileshe (2012)		X		
73	Olofsson et al. (2007)		X		
74	Pan (2012)			X	
75	Park et al. (2017)		X		
76	Pasquire et al. (2002)			X	
77	Pellinen (2016)		X		

No	Academic researches	Construction performance/ Productivity publications	BIM in construction publications	OSM in construction publications	BIM–OSM Interaction confirming publications
78	Poririer et al. (2015)	X			
79	Popov et al. (2010)		X		
80	Porwal and Hewage (203)			X	
81	Sacks et al. (2010)	X			
82	Sacks et al. (2009)	X			
83	SBEnrc (2017)			X	
84	Shin et al. (2016)			X	
85	Segerstedt and Olofsson (2010)	X			
86	Smith (2014)		X		
87	Succar et al. (2009)		X		
88	Sulankivi et al. (2010)	X			
89	Takim and Akintoye (2002)	X			
90	Trani et al. (2015)		X		
91	Vernikos et al. (2014)				X
92	Walker (2018)	X			
93	Wang et al. (2015)		X		
94	Wang and Love (2012)		X		
95	Wang and Chong (2016)				
96	Wong and Fan (2013)		X		
97	Wong and Fan (2014)		X		
98	Wynn et al. (2013)				X
99	Zhang et al. (2010)		X		
100	Zhang et al. (2013)		X		

Table 5.1b *Summary of the papers on BIM, OSM and performance*

Research categories	Number of the papers
BIM specification and capabilities in construction	50
OSM specifications and capabilities in construction	16
BIM–OSM interactions confirming papers	7
Construction performance/productivity	27
Total papers	100

5.4.1 The standalone OSM capabilities/functions for KPrIs.

Table 5.2 summarises the indicators that can be improved using standalone OSM techniques, and reflects the relevant KPrIs in Figure 5.1. The following sections discuss the ways in which the nominated KPrIs can be improved under OSM functionalities.

Table 5.2 *Nominated KPrIs affected by OSM functions*

The nominated KPrIs variables from Figure 4.1	The KPrIs' signifier	Number of sources of evidence contributing to effect on the variables	Sources contributing to the justification of interactions
Planning and scheduling	D4&D5	3	Elnaas et al. (2014); Lessing et al. (2005); SBEnrc (2017)
Safety	D11	2	Blismas et al. (2005); SBEnrc (2017)
Marketing	D14	2	Pan et al. (2012); SBEnrc (2017)
Cost control	D9	2	Pasquire& Connolly (2002); SBEnrc (2017)
Site management	D1	2	Arashpour et al. (2015); Meiling et al. (2012)

Sustainability	D9/D16/K1	3	Abanda et al. (2017); SBEnrc (2017); Boyd et al. (2012)

5.4.1.1 Planning and scheduling.

Low-quality construction may result in rework or modifications. As manufactured components are simply attachable in construction sites, rapid erection will shorten the construction process (SBEnrc, 2017). Also, quality control may be more feasible and precise in a controlled environment, due to better accessibility to the tools required for quality measurement to comply with specifications (Elnaas et al., 2014). Thus, the chances of any rework or correction being required on the site can be minimised. In addition, the construction process can be simplified if it follows a smoother plan and schedule, which leads to quicker completion. Off-Site Manufacturing has rectified many problems in the construction industry, as well as improving planning, scheduling and control, both off-site and on-site activities. These optimisations are beneficial and productive in OSM-based construction projects (Lessing et al., 2005) compared with non-OSM-based projects. Therefore, planning and scheduling of services, such as supply, transportation and human resources management are able to be improved in OSM-based projects.

5.4.1.2 Safety.

Occupational health and safety regulations are more easily observed in a controlled working environment, such as a factory (Blismas et al., 2005). Injuries arising from falls and collisions are more avoidable in these conditions, as the necessary safety considerations are easier to meet (SBEnrc, 2017). Also, it is logical that the reduced on-site activities required in an OSM-based project will result in fewer construction crew members being required on the site, thereby reducing the likelihood of injuries.

5.4.1.3 Marketing.

Marketing is improved by attracting more clients/stakeholders. To be more specific, promising a quicker construction period, along with high-quality products, is attractive to homebuyers, who assume that earlier construction completion and settlement in their homes will help them pay less rent and save more. This is also attractive to investors, in that they will expect to achieve a quicker return on their equity, while more rapid completion results in a project being sold more quickly. Consequently, more rapid cash flow and capital return and re-investment will occur, which is especially important for commercial projects (SBEnrc, 2017; Pan et al. 2012).

5.4.1.4 Cost control.

The 24-hour availability of materials in the site store prevents delays due to the ordering process. The longer the completion, the greater the overhead costs. Conversely, not only will the costs of multiple orders be eliminated, but also the purchase of a large volume of materials at lower prices is possible. The cost of waste management is another issue that is avoidable once waste and reuse-related issues are handled by the factories. For example, no dumping costs are imposed (SBEnrc, 2017). In a controlled environment, the chance of material protection is maximised, resulting in an economical material cost due to material storage optimisation (Pasquire and Connolly, 2002). In other words, any possibility of material damage arising from weather conditions and the probability of vandalism, theft and mistakes as a result of human handling are minimised.

5.4.1.5 Site management.

Reducing on-site construction activity and reducing congestion in these activities also reduces human errors, resulting in better and more efficient site management (Arashpour et al., 2015; Meiling et al., 2012).

5.4.1.6 Sustainability.

More controllable production reduces the chance of material wastage. This contributes to environmental sustainability (less waste) and economic sustainability (reduced costs due to less material usage). Energy consumption is also more efficient due to more controllable on-site equipment and energy savings resulting from less trade and activity disruption (Abanda et al., 2017). Safety considerations are promoted in a factory environment. Further, workers can be provided with a comfortable environment, as they do not work in severe weather conditions. This is associated with social sustainability (SBEnrc, 2017). Each of these sustainability factors comply with the ‘people’ principles of OSM (Boyd et al., 2012).

5.4.2 The standalone BIM capabilities/functions for KPrIs

This section presents the KPrIs that contribute to improving a project via standalone BIM functionalities. Table 5.3 presents the nominated KPrIs, as shown in Figure 4.1.

Table 5.3 *Nominated KPrIs affected by BIM functions*

The nominated KPrIs from Fig 4. 1	The KPrIs' signifier	Number of sources of evidence contributing to effect on the variables	Sources contributing to the justification of interactions
Sequence /Process management	D17	2	Chen & Luo (2014); Wang & Love (2012)
Site allocation & accessibility	D1	2	Hergunsel (2011); Vernikos et al. (2014)
Planning& Scheduling	D4&D5	5	Barati et al. (2013); L. Ding et al. (2014); Kang et al. (2007); Hergunsel (2011); Li et al. (2014)
Safety	D11	3	Chen & Luo (2014); Khoshnava et al. (2012); Ghazali& Irsyad (2016); Sulankivi et al. (2010)
Social Sustainability	K1	3	Ciribini et al. (2015); Wong & Fan (2013); Eastman & Sacks (2008)
Economic Sustainability	D9, C3& F7	3	Wong & Fan (2013); Azhar et al. (2009); Ahmad and Thaheem (2018)
Environment Sustainability	D16	2	Wong & Fan (2013);Lu et al. (2017)
Interface management	D10&D7	2	Smith (2014); Olofsson et al. (2007)
Procurement& contract	G7	1	Sacks et al. (2010)
Information data	H3,5,8,9&D10	2	Hamdi & Leite (2012); Succar (2009)
Value engineering	I2	2	Park et al. (2017); Shin et al.(2016)
Concurrent engineering	I4	2	Pellinen (2016); Succar (2009)

5.4.2.1 Sequence/process management

Under the BIM approach, information-sharing between stakeholders links all the parties involved in a project, including the designer and the contractor, in a virtual 3D model with BIM management tools revealing all the related details. All parties are able to communicate easily to clarify any ambiguities or confusion (Chen & Luo, 2014; Wang & Love, 2012).

5.4.2.2 Site allocation and accessibility

The virtual site space created by BIM gives a good understanding of the 'site logistic plan' (Hergunsel, 2011). This is enables the effective organisation of the use of every location on the site in terms of the optimum layout of temporary offices, material stock, siting equipment and plant, among others (Vernikos et al., 2014).

5.4.2.3 Planning and scheduling

Effective identification of potential problems affecting project planning and scheduling is possible via a 3D BIM model, as all parties involved in a project are linked through working on the same model at the same time and exchanging relevant information (Barati et al,. 2013; Ding et al., 2014; Kang et al,. 2007). The application of the critical path method and line of balance improve scheduling in BIM (Hergunsel, 2011).Through BIM, optimum resource management, which plays a significant role in cost control, is achievable. Therefore, scheduling can be improved via BIM (Li et al., 2014). This can be observed in both general planning/scheduling and re-planning/re-scheduling.

5.4.2.4 Safety

When site activities are better organised there are fewer the incidents resulting from site disruption. Through the virtual site environment model offered by BIM, safety considerations are more observable through a 'dynamic safety analysis' (Chen & Luo, 2014); in particular, modelling of crane operation via BIM for site accessibility (Khoshnava et al., 2012), for materials transfers, plant operations and equipment movement, all of which will improve safety management. A 4D-BIM model provides an optimum site layout and more effective safety plans (Sulankivi et al., 2010), which can be 'a starting point for safety planning and communication' (Azhar et al., 2012, p.83).

5.4.2.5 Social sustainability

The 3D model offered in the BIM system enables designers to invite clients to review and impose any probable changes to a project to satisfy their needs and bidding offers. Feedback from clients is received before the commencement of construction, which not only prevents delay but also saves money, because any changes requested after construction begins may be costly (Ciribini et al., 2015). The increased safety offered via BIM can be considered social sustainability, as workers are in a safer environment. This can also be considered a social factors in workers' lives (Wong & Fan, 2013), in that social sustainability focuses on people's convenience (Eastman & Sacks, 2008).

5.4.2.6 Economic sustainability

Through the virtual model offered by BIM, design and construction management can be streamlined and improved (Wong & Fan, 2013). To achieve this, the best decisions must be made for a project. For example, accurate information about the materials required minimises budget waste arising from the purchase of superfluous materials. The possibility of safety alerts also minimises the chances of compensation payouts being necessary due to falls and collisions. Azhar et al. (2009) stated that BIM returns 634–1633% of the initial investment. This confirms the satisfaction of economic sustainability considerations. Ahmad and Thaheem (2018) also highlighted the economic sustainability achieved in building energy consumption when BIM was implemented.

5.4.2.7 Environment sustainability

Materials are not wasted once there is no requirement for construction correction. More organised sites result in more efficient and effective activities, saving material and energy (Wong & Fan, 2013). In fact, the optimisation of energy and material consumption achieved via BIM implementation can protect the natural environment and reflects both economic and environmental sustainability (Lu et al., 2017).

5.4.2.8 Interface management

The ability to exchange readable data, subject to a compatible format, between the parties involved promotes a professional interface and effective linking between stakeholders (Smith, 2014). An informative link between the plumbing, electrical and mechanical systems is a constructive collaboration on construction sites. The conflicting activities of different teams sometimes affect each team, leading to the need for rework. This problem is rectifiable by BIM (Olofsson et al., 2007), which offers interface management possibilities.

5.4.2.9 Procurement and contracts

Lack of a procurement system and contracts suitable for BIM implementation is a barrier to achieving the full benefits from the adoption of BIM, which offers reforms on both the procurement and contract sides. The nature of information-sharing in the BIM environment specifies every action required by all parties involved in a project (Sacks et al., 2010). The definition of any likely required provision can be clearly given in the contract once the commitments of each party are specified. The party responsible for any defects or required actions is observable if the activities are monitored and traced via the BIM environment, which prevents disputes and contract complexity.

5.4.2.10 Information data flow through virtual model quality and data richness

In addition to a quality virtual model generating accurate information, a rapid line of communication for the exchange of data are provided by the BIM model (Hamdi et al., 2009). This removes any doubts regarding the requested specification of materials and elements and their integrity. Moreover, this function is also able to bridge the divide between academia and industry to allow further improvement of BIM guidelines as it is being practised.

5.4.2.11 Value engineering

A BIM-based value engineering (VE) idea bank enables stakeholders achieve rapid data retrieval from past experience at the idea generation phase (Park et al., 2017). Further, the nature of this information-sharing platform links the stakeholders to each other to assess the consequences of a design or apply alternatives. In other words, an assessment of the feasibility of every change in terms of technical and cost factors is possible immediately via this smart virtual model, as the other parts of the model automatically update themselves with the changes. Under the VE process, the virtual model can return to the baseline by an undo function, with no money, energy or time being spent in reality. This confirms the sustainability aspects of a BIM-based VE (Shin et al., 2016).

5.4.2.12 Concurrent engineering

The theme of concurrent engineering can be clearly seen in BIM if there are the opportunities to fast-track activities or carry them out in parallel (Pellinen, 2016; Succar, 2009). As an example, the process of reviewing and confirming the designs, in terms of executive technical requirements, can be shortened by combining the models virtually (reviewing processes at the same time) rather than handing over the models sequentially and undertaking a paper-based model evaluation.

5.4.3 The interaction of BIM and OSM for KPrIs

Table 5.4 presents the potential OSM–BIM interactions. It justifies how these interactions occur and improve KPrIs once both techniques are applied simultaneously. The KPrIs to be improved are listed in the left column. The next column presents the relevant KPrIs from Figure 5.1, while the third column presents the sub-sections explaining OSM–BIM interactions. Lastly, the fourth column reveals the sources contributing to the justification of the OSM–BIM interactions.

Table 5.4 *A summary addressing the improvements achieved via OSM–BIM interactions*

The nominated KPrIs for improvement from Figure 4.1	The KPrIs' signifier	The interactions descriptions No via OSM–BIM implementation	Sources contributing to the justification of interactions
Sequence /Process management	D17	Interaction 4.3.1	Lu and Korman (2010); Irizarry (2013)
Site allocation & accessibility	D1	Interaction 4.3.2	Vernikos et al. (2014); Trani et al. (2015)
Planning& Scheduling	D4&D5	Interaction 4.3.3	Bank et al. (2010)
Safety	D11	Interaction 4.4.4	Zhang et al. (2013); Irizarry et al. (2013); Zhang et al. (2010)
Social Sustainability	K1	Interaction 4.4.5	Wong & Fan (2013)
Economic Sustainability	D9, C3& F7	Interaction 4.4.6	Wang& Chong (2016)
Environment Sustainability	D16	Interaction 4.4.7	Wang& Chong (2016); Wong & Kuan (2014)
Interface management	D10&D7	Interaction 4.4.8	Smith (2014)
Procurement& contract	G7	Interaction 4.4.9	Barlish & Sullivan (2012)
Information flow via virtual model quality& data Richness	H3,5,8,9&D10	Interaction 4.4.10	Haron et al. (2010); Ezcan et al (2013); Lee et al. (2015); Popov et al. (2010); Sacks et al. (2010)
Value engineering	I2	Interaction 4.4.11	Forgues et al. (2012)
Concurrent engineering	I4	Interaction 4.4.12	Goulding et al. (2015)

The following sections discuss how these two techniques may interact constructively throughout a project.

5.4.3.1 Sequence/process management

The information-sharing capability in BIM will remove the issue of fragmentation between the different parties involved in a project (Lu and Korman, 2010). The sequences of OSM-based projects include design, order, component production, transfer and the installation process. As has been explained, BIM is capable of improving construction supply chain management through an integration process. The effective monitoring of resources is possible by linking and visually representing the process (Irizarry, 2013). As Irizarry (2013, p.241) claimed, providing the digital geographic information of a construction site enables experts to sequentially keep track of the ‘flow of materials, availability of resources, and map of the respective supply chains’. The manufactured components can also be deemed as the material in OSM-based projects. This optimises the identification of manufactured components at the stocking and dispatching stages.

5.4.3.2 Site allocation and accessibility

The virtual visualisation of objects provides the contractor a rapid and improved visual evaluation when comparing the planned and actual specifications and allows easier identification of any failure in the arrival of components. Thus, the placement of faulty and sound components is organised efficiently upon their arrival (Vernikos et al., 2014). Organising and assigning space to every group of components via a virtual space is more practical for organising the site in terms of accessibility to both the components and the relevant area of the site (Trani et al., 2015).

5.4.3.3 Planning and scheduling

The manufacturer, as a part of the project team, is linked to the other parties, not only in the main planning and scheduling of the project, but also in the case of any rapid changes. A collaborative environment and information-sharing platform for ‘early decision-making’ (Bank et al., 2010) is the main capability of BIM, playing a dominant role in both the main planning/scheduling phase, and any correction planning/re-scheduling.

5.4.3.4 Safety

Under effective management of the activities in a BIM–OSM project, all activities are optimally organised and formulated, thereby reducing complexity, which results in fewer accidents. Modelling of the assembly of the prefabricated components in BIM enables contractors to review the erection and positioning process virtually, which may reveal any potential unobserved safety shortcomings (Irizarry et al., 2013). The likelihood of falls (Zhang et al., 2013) and collisions due to plants operations in OSM-based projects is high due to the dispatch and movement of components dispatch on the site. BIM is able to reveal the probable fall situations from heights, identify the best access routes for plant operations, and offer lifting drawings for crane activities, which will minimise the chances of reportable incidents (Zhang et al., 2010).

5.4.3.5 Social sustainability

BIM enables a constructive interaction between designers, manufacturers and contractors by offering accurate information in terms of the units' quality specifications and properties, which can be deemed as comfort in the professional life (Wong & Fan, 2013). This reflects an easing in professional life, equivalent to social sustainability.

5.4.3.6 Economic sustainability

Flexibility in an OSM-based project is highly limited once the units are transferred to the construction site. Through the capability of clash detection and accurate data via BIM in an OSM-based project, the chance of any extra activities required for rework is limited. Since any rework comes with excessive use of workforce, equipment, plant and material removal and reuse, minimising the chance of rework satisfies the aspects of material waste as well as work hours (Wang and Chong, 2016).

5.4.3.7 Environmental sustainability

Material usage is more efficient and accurate in a controlled environment. On the basis of an exact quantity of material determined via BIM, both the chance of material waste and rework are minimised, satisfying environment sustainability requirements (Wang & Chong, 2016). The construction site is more organised once the job shifts from the factory to the construction site. In fact, the workspace is more efficient due to the reduced number of activities required and the smaller workforce compared with a more congested traditional construction site. The need for fewer trades working at the same time results in less noise and less emissions from equipment. Reduced on-site activity also means more efficient energy consumption. Thus, it can be claimed that BIM is effective from the point of view of environmental sustainability (Wong & Kuan, 2014).

5.4.3.8 Interface management

BIM provides a constant communication line with the other parties, including designers, construction contractors (Smith, 2014) and manufacturers that is accessible with no waiting time. Therefore, information and data are exchangeable with manufacturers, as parties involved in a project, in the form of readable formats consistent with BIM.

5.4.3.9 Procurement and contracts

A BIM-based contract in an OSM-oriented project carries significant responsibility for the parties involved in meeting the project requirements, from data production to executive operations, as fragmentation between the design and delivery teams can be controlled at an early stage. No time is wasted on disputes to identify the party responsible in case of errors or failures, as the organisational structure is clear. Also, in the case of any changes, the manufacturer can be notified more rapidly due to the BIM information-sharing platform, and the production line can be immediately modified to take the steps required for the change because under a BIM model, the management of the drawing process and any technical review is more rapid than with other techniques (Barlish & Sullivan, 2012). Thus, the determination of responsibility for faulty components can be managed within the contract.

5.4.3.10 Information data flow through virtual model quality and data richness

The capacity of BIM to provide transparent and accurate specifications, as well as to share data, enables the manufacturer to participate in the assembly guideline definition, indicating the exact procedures to position manufactured components. This capability originates from ‘model quality and data richness’ (Haron et al., 2010). It enables the manufacturer to efficiently recognise all the parts of a component for the purpose of assembly (Ezcan et al., 2013), which is important for contractors on the construction site. This confers simple accessibility and easy observation of data and thus an effective data flow (Lee, Eastman, & Lee, 2015) between the designers, the contractors and the manufacturers. In addition, under BIM the ability to identify repetition enables designers and manufacturers to recognise more automation opportunities for ‘series production’, resulting in cost saving due to ‘virtual object-oriented design’ (Popov et al., 2010; Sacks et al., 2010).

5.4.3.11 VE

The effect of changes to manufactured components (constructability) can be assessed under a BIM model, which also allows cost evaluations (Forgues et al., 2012) prior to any actions in the real project (feasibility via VE). It can be claimed that VE is much more effective for VE than merely brainstorming via paperwork. Therefore, VE is achievable in a BIM–OSM-based project.

5.4.3.12 Concurrent engineering

Concurrent engineering has been introduced to the industry as one of the techniques able to reduce project process time through fast-tracking activities or running activities in parallel (Goulding et al., 2015). For example, the components may be produced while site preparation is in progress. Concurrent engineering is achievable within OSM–BIM projects on the assumption that any incompatibility of components would disturb the fast-tracking plan (running activities in parallel) in OSM-based projects. By providing the exact specifications for all components and continuous information-sharing and communication between the designer, contractor and manufacturer, the chances of on-site rework efforts to rectify or adjust components, as well as the chance of rejection of components, is minimised. Thus, the fast-tracking plan for concurrent engineering is not hindered in OSM–BIM projects.

5.5 Integrated Framework

This research has highlighted the interactions between OSM and BIM and their contribution to construction performance in a broader sense, as well as to construction productivity in a narrow sense. It has justified each capability of OSM and BIM independently, as well as the capabilities of the concurrent application of OSM–BIM (OSM–BIM interactions), respectively. Figure 5.4 illustrates the integrated framework that leads to improved overall project performance. It consists of three stages: input, process and output. At the input stage, the data are derived from the capabilities of BIM and OSM that have the potential to interact with each other. It shows that the concurrent application of the capabilities that have the potential for OSM–BIM interactions (POBIs) can result in improved KPrIs, subject to their systematic adoption. Systematic adoption refers to the proper and concurrent practice of the techniques' capabilities at both the design and the construction stages. The improvement measures result in overall project performance. It is expected that construction professionals can improve project productivity by considering the 12 KPrIs through the interactions of BIM and OSM (as shown in process stage). The KPrIs may be addressed by interactions through the optimisation of the work breakdown structure at the design and construction stages. Subsequently, the technical specifications and contractual requirements can be formulated before the construction stage so that these interactions can be applied.

Low productivity has always been one of the main challenges for the stakeholders in the construction industry, particularly from the continuous improvement perspective. The proposed integrated framework provides useful references to the potential productivity areas that need to be targeted in a project, and which may help to achieve the highest level of project productivity and performance. It also promotes the effective adoption of BIM and OSM in the future.

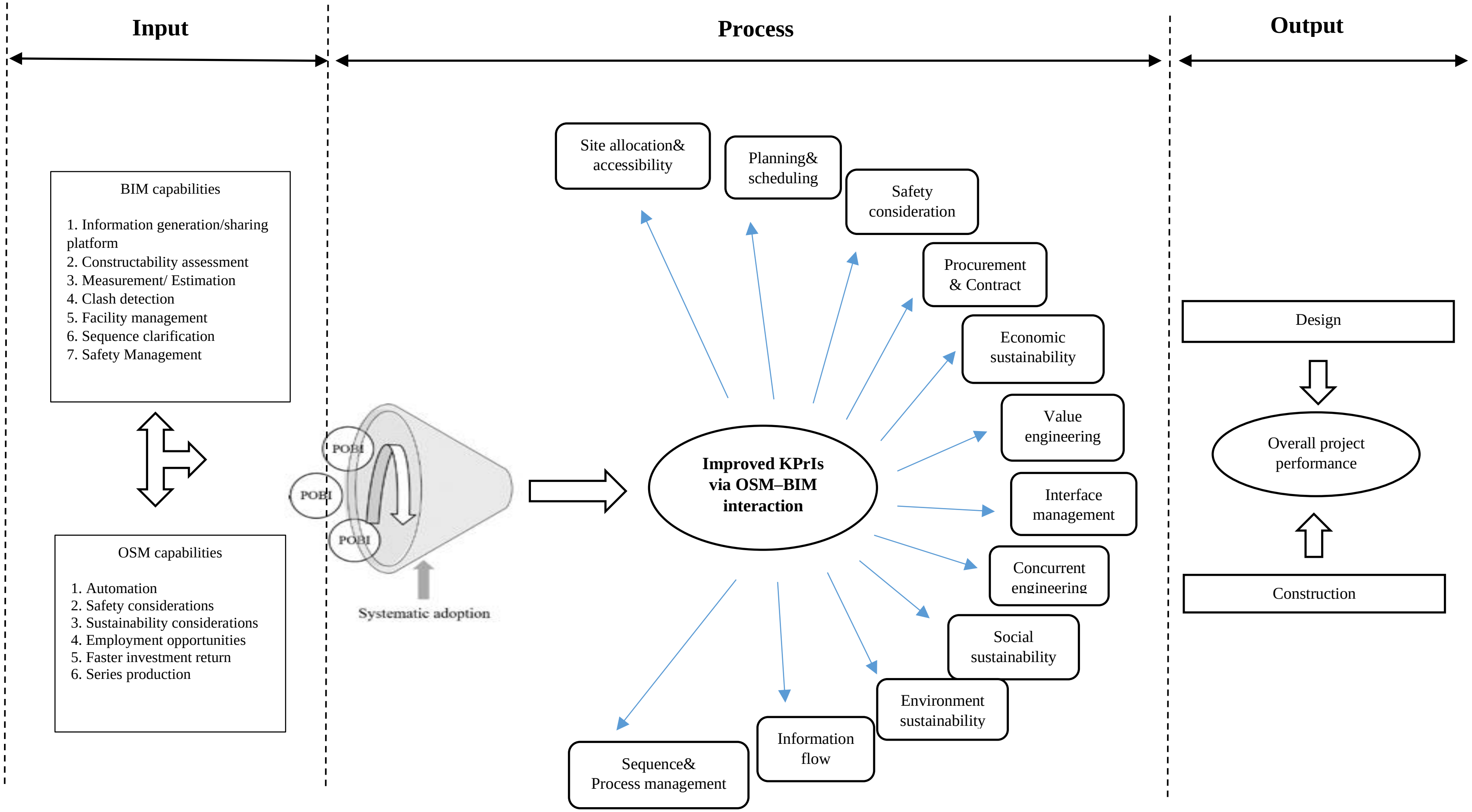


Figure 5.4. Integrated framework of OSM–BIM interactions for productivity improvement.

5.6 Discussion and Conclusion

This research project has critically reviewed the literature in order categorise KPrIs for construction projects, and identified the indicators that can potentially be used to improve productivity and performance via the capabilities of OSM and BIM, both independently and together. It has addressed seven BIM-based capabilities and six OSM-based capabilities individually, as well as 12 POBIs relevant for KPrIs improvement from the productivity perspective. Figure 4.3 showed a scoping review was used to identify these capabilities, and 100 journal articles were carefully analysed under four main research categories: construction productivity/performance, BIM in construction, OSM in construction and OSM–BIM interactions. This revealed the capabilities of the OSM and BIM techniques, and 12 potential interactions to achieve KPrIs improvement within ten categories: company characteristics, materials, labour, management, regulation, machinery, contract condition, information technology, engineering and external circumstances.

The main advances of this scoping review paper are: (a) the first systematic discovery of the 12 potential interactions between OSM and BIM and their benefits in productivity improvement; and (b) the integrated framework (Figure 4.4) that addresses KPrIs improvement at the design and construction stages. The related previous studies have only briefly discussed the integration of BIM and OSM at a preliminary stage of the building processes (Nawari et al., 2012), the management drivers (Vernikos et al., 2013), the required BIM functionalities (Ezcan et al., 2013), and the potential benefits (Goulding et al., 2012; Amanda et al., 2017). The identification of these interactions between BIM and OSM extends the existing body of knowledge, especially for the effective implementation and management of OSM–BIM-based projects. The productivity indicators identified as useful for improvement by OSM and BIM can serve as a guideline and benchmark for organisations, which they can use to streamline their resources and operations to enable them to achieve the desired outcomes of their projects. Moreover, the findings of this paper are generalizable to both developed and developing countries.

However, certain limitations need to be considered, such as the exclusion of the latest publications in the proposed four research categories, the lack of empirical research in recognising the degree of impact and practicability of the OSM–BIM interactions, and for the prioritisation of each key productivity indicator. Future research could investigate the complex cause-effect relationships between BIM and OSM capabilities and their interaction. As a part of a larger research project, this paper will be followed by statistical analysis using Structural Equation Modelling (SEM) to reveal the degree of practicability of these interactions. A range of hypothesised interactions will be evaluated and judged by experienced practitioners. The results of these investigations will be applicable to improving the planning and managerial stages for productivity improvement in OSM-based projects. A case study would be complementary to the current research to evaluate the practicability of the interactions and to uncover potential barriers in the pathways of OSM–BIM-based projects.

Chapter 6: Appraisal of Potential Interactions Between Building Information Modelling and Off-Site Manufacturing for Project Performance

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Abstract

The high demand for improvements in construction productivity has led to the emergence of advanced techniques such as building information modelling (BIM) and off-site manufacturing (OSM). Many studies have discussed the individual capabilities of BIM and OSM, but limited studies have qualitatively and quantitatively explored the concurrent application of these techniques. In this study, an in-depth evaluation was conducted to determine the influences of OSM–BIM interactions on overall project performance. Structural equation modelling method was adopted to examine the complex relationships among research variables based on survey data. Survey respondents comprised construction practitioners across Australia. The results show that the individual application of OSM or BIM had no significant influences on the overall project performance, but a systematic adoption of the interactions as a mediator between OSM and BIM, significantly enhanced the overall project performance as measured by key productivity indicators. The technicalities of these interactions are applicable at the planning and managerial stages, enabling efficient project functioning in hybrid OSM–BIM-based projects. From the broader perspective, the research also contributes to the diffusion of innovation in the construction industry.

Keywords: Systematic adoption, construction productivity, interactions.

6.1 Introduction

The construction industry is a major contributor to the economy of countries (Klufallah et al., 2018). Countries have upgraded construction methods, aiming to respond to the demand for a sustainable level of construction productivity that contributes to the economic growth (Hosseini et al. 2018). The observed decline in construction productivity has challenged economy and resulted in the emergence of new techniques (Dolage & Chan, 2013). The search for such techniques has prompted management to consider ways of addressing factors that contribute to poor productivity. Fragmentation among project stakeholders is at the root of poor productivity. Yahya (2010) found that modern construction techniques could resolve malfunctioning systems in construction projects. Many construction companies aim for an efficient flow of accurate information among project stakeholders at both the pre-construction and construction stages to improve quality (Zeng, Lou, & Tam, 2007) which is an aspect of performance. The application of advanced techniques has been observed to improve the efficient flow of information. Quick and efficient responses from stakeholders is a key factor in project value creation. Improved control over activities is another means of eliminating inefficiencies that may occur in dynamic environments such as construction sites (Kenley, 2014). Building information modelling (BIM) and off-site manufacturing (OSM) have been identified as two revolutionary techniques capable of addressing the issues threatening construction productivity.

A hybrid team compromises planner, designer, contractor (Hosseini et al. 2018), and manufacture as project stakeholders in a construction project. The quality of communication among these project stakeholders plays an essential role in project progress (Hosseini et al., 2016). BIM provides these parties with an accurate information-sharing platform for reliable communication (Hosseini et al., 2017) and the ability to visualise project status, resulting in the efficient coordination between parties involved in projects. The United States and United Kingdom (UK) have developed regulations and standards on BIM adoption, supporting its applicability (Lea et al., 2015). Indeed, the UK government has mandated that all public sector projects adopt a minimum of level 2 BIM (Khosrowshahi & Arayici, 2012). OSM provides a more controlled working environment and standardised building components. It was developed to optimise resource utilisation, meet higher expectations of quality, accelerate production lines and increase the effectiveness of safety measures, which together contribute to higher productivity levels (Blismas, 2007). Applied individually, these techniques have not been observed to cover all aspects of productivity; however, when applied concurrently, the interactions between these two approaches have been found to satisfy more areas of productivity.

Sabet and Chong (2018) clarified the boundaries between productivity and performance, claiming that performance outcomes may be met by improving productivity indicators. From this perspective, both techniques are justifiable for improving productivity indicators and final project performance. However, efforts to implement OSM and BIM have so far failed to fulfil their objectives because of the lack of research advising on their systematic adoption. Technological evolution takes time, and concrete evidence of the practical value of new techniques and innovations is needed. Goulding et al. (2012) developed an enriched BIM model to fill the gaps in OSM-based projects such as poor linkages between people, processes and technologies. BIM links the design, manufacturing and construction stages, enabling all parties to access relevant data (Nawari et al., 2012). These linkages have changed traditional practices in the construction industry. Amanda (2017) highlighted the enormous benefits of BIM–OSM-based projects compared with traditional construction projects.

Yin et al. (2019) identified a range of research gaps in BIM for OSM. Therefore, the supporting objectives to achieve the overall aim are: (a) to examine the influences of the standalone capabilities of OSM and BIM on project performance via key productivity indicators (KPrIs); and (b) to develop the interactions between OSM and BIM and determine the influences of these interactions as a mediator between the two approaches on overall project performance via the improvement of KPrIs. Structural equation modelling (SEM) was the approach to analyse data. A questionnaire survey was used as the data collection tool. Respondents were construction practitioners familiar with OSM and BIM in Australia. This study aims to highlight the practicalities of the interactions between the two approaches to encourage clients and practitioners to embrace OSM–BIM-based projects. The study also provides insights on technical details at the planning stage to improve the management of hybrid OSM–BIM-based projects.

The rest of this paper is structured as follows. Section 2 discusses the need for improved construction productivity. BIM–OSM interactions are offered as possible solutions. Section 3 focuses on the primary research model and development of hypotheses. Section 4 presents the research approach and stages and the application of SEM. Section 5 presents the data analysis and findings. Section 6 concludes the paper.

6.2 Literature Review

6.2.1 Construction productivity.

Productivity issues in the construction industry have been flagged for a long time. Efforts toward industry innovation have not addressed the need to improve productivity indicators (Barbosa et al., 2017). In addition to innovating in projects, it is crucial to adopt a range of productivity fundamentals (Sabet & Chong, 2020). Sabet and Chong (2020) argued that a lack of integrated management, competent workforce, modernised equipment or strategies of adoptability, and an inappropriate or partial technique application may impede productivity trends. Productivity has many aspects—all of which should be addressed for successful productivity outcomes. Sabet and Chong (2018) categorised KPrIs into "company characteristics, materials, labour, management, regulation, machinery, contract condition, information technology, engineering and external circumstances" (p. 18). They discussed that an improvement in these indicators results in better productivity and enhanced final project performance. The in-project application of some techniques affects KPrIs directly, while others have an indirect effect. However, productivity levels are not yet satisfactory because emerging techniques can only cover some of these KPrIs (Sabet & Chong, 2019). This means that productivity continues to lag behind demand. Javed et al., (2018) considered productivity the ratio between resource input and construction output. Resistance to change is at the root of unsuccessful efforts to improve construction productivity (Lines et al., 2015). Ineffective changes are associated with potentially costly errors, so practitioners and authorities consider change risky (Motawa et al., 2006), and are often unwilling to implement new practices. Therefore, innovations have not been systematically implemented or have only been partially practiced (Hall, Algiers, & Levitt, 2018). Among the emerging approaches to productivity improvement, OSM and BIM have attracted the attention of authorities as being capable of significantly improving productivity and overall project performance. Hamdan et al. (2015) found that the concurrent application of these two approaches offers a wide range of capabilities that lie in more areas of productivity.

6.2.2 Project Performance

The desire for project performance to secure profitability for stakeholders, clients, and end-users has resulted in upgraded construction methods. However, the ever-changing nature of the construction industry challenges the adaptability of these techniques. It also challenges the practicality of a technique's capabilities within a system (Ferrada & Serpell, 2013). Further, this dynamic environment may disturb the progress of a project, by challenging the line of communication between stakeholders and data flow (Holt, 2015). Therefore, inefficiencies in time, cost, safety, and quality may be unavoidable. The consequent dissatisfaction among stakeholders gives rise to disputes within a project, which further impede the expected level of project performance. Walker (2018) stated that a collaborative environment is crucial for enhancing the performance level of a project, while Jha and Iyer (2006) asserted that the factors of time, cost, quality, safety, and stakeholders' satisfaction compromise overall project performance. In the literature surrounding project performance, "performance" and "productivity" are used interchangeably (Dozzi& AbouRizk, 1993). In other words, these two schemes are alignment with each other.

6.2.3 Background on OSM.

The modernisation of construction has seen the emergence of OSM in which standardised construction components are produced, transported and assembled at construction sites. A considerable attention to OSM have been paid to the market of UK, Malaysia, Hong Kong, China and Australia (Li et al., 2014). Other terms for OSM include industrialised building and prefabrication (Khalfan & Maqsood, 2014). Tam et al. (2007) found that OSM significantly reduces not only waste but also cost and time because fewer resources need to be allocated to waste management. Arif and Egbu (2010) found that the use of preassembled components optimises quality, reduces the need for resources, improves health and safety, increases the integration of project stakeholders and reduces the cost of the final product. Volumetric and non-volumetric preassembly are applicable at different stages of construction and include prepared concrete, structural components, wall panels, mechanical and electrical parts, and even complete units (Li et al., 2014). Overall, a wide range of joinery parts, including volumetric, non-volumetric components and building services, are available for assembly in construction projects (Blismas & Wakefield, 2009). Many studies have been carried out on OSM in the last decade, but there is still room to improve operational, management and strategic considerations to make OSM more applicable in the construction industry (Hossieni et al., 2018).

6.2.4 Background on BIM.

BIM is a very considerable innovation that has extensively appeared in the architecture, engineering and construction industry (Issa & Olbina, 2015; Hossieni et al., 2018). It refers to ‘a new approach to design, construction, and facility management in which a digital representation of the building process is used to facilitate the exchange and interoperability of information in digital format’ (Mutis et al., 2018, p. 137). Some governments have identified and recommend BIM as an effective strategy to address construction productivity failure. As a pioneer of BIM, the UK has mandated the application of level 2 BIM in government projects (Love et al., 2015). Irizarry et al. (2012) point out that the major capabilities of BIM are the visualisation of construction status and access to exchangeable information by project stakeholders. Hossieni et al., (2017, p. 1) discussed that BIM transformed facility management by providing ‘different forms of data and information’. The adoption of BIM has rapidly increased, and different companies apply various levels of BIM with respect to expertise and client demands (Jung & Lee, 2015). Due to the BIM’s influential capabilities, the role of BIM and its application are worth undergoing further analyses from the perspective of diffusion innovation theory (Hosseini et al., 2018).

6.2.5 Interaction between OSM and BIM.

BIM offers rich, supportive information management abilities, enabling it to facilitate other innovative techniques and building methods (Abanda, Tah, & Cheung, 2017; Ezcan et al., 2013). The systematic adoption of BIM with other approaches may provide overlapping capabilities, maximising the functionality of both approaches. This concept accelerates the maturity of BIM, resulting in the operational and strategic extension of BIM implementation (Khosrowshahi & Arayici, 2012). For example, BIM can be effectively paired with lean construction techniques to provide a collaborative environment (Sacks et al., 2010). Wynn et al. (2013) found that the information technology–based nature of BIM can enhance the efficiency of OSM. The lack of empirical studies on the applicability of BIM in OSM means that the relationship between these two approaches is unclear (Tang et al., 2019). Sabet and Chong (2019, p. 7) have highlighted the potential for collaboration between the two approaches, resulting in 'faster progress, quality, safety, cost optimisation, and minimisation of work correction on site' or, broadly, a more sustainable project from the concept to construction stages. However, Jang and Lee (2018) argue that coordination between mechanical and electrical systems at construction sites is a time-consuming process that requires additional person-hours because of some required adjustments in the assembly stage. Therefore, the coordination of activities plays a vital role in the successful establishment of OSM–BIM systems. Ezcan et al. (2013, p. 7) have argued that 'providing an improved design, facilitating collaboration and covering accurate and extensive amounts of information' seem to be the most useful benefits of BIM in OSM-based projects'. Nawari (2012) claims that BIM standards and provisions specifically designed for OSM can guarantee efficiency and productivity in OSM-based projects. Vernikos et al. (2014) demonstrated that BIM is capable of improving OSM, but its application in OSM has been limited. The lack of evidence on the potential applicability of BIM in OSM has been flagged as a reason for construction clients and practitioners being unmotivated to apply the full capacity of BIM in OSM (Abanda et al., 2017; Gibb, 2014). Liu, Chen and Al-Hussein (2019, p. 84) have identified ‘BIM-based generative design for prefabrication’ as one of the areas requiring further research.

6.3 Research Model and Hypothesis Development

Given the lack of sufficient research studies quantifying the relationships between BIM, OSM and KPrIs, a hypothetical model comprising four constructs was developed for the present study (see Figure 6.1). As Figure 6.1 shows, the standalone capabilities of the two approaches as well as their interactions play the role of independent variables, while overall project performance (reflected by KPrIs as discussed earlier) is the dependant variable in the research.

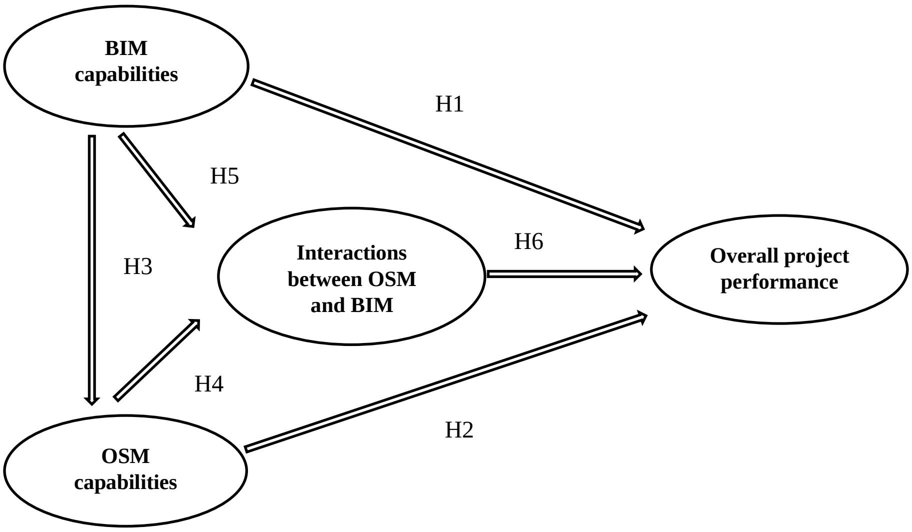

Figure 6.1. Hypothetical research model.

6.3.1 BIM and project performance.

BIM is an approach in which the integration of graphical and non-graphical information enables project stakeholders to collaborate more efficiently throughout a project’s life cycle (Pezeshki et al., 2019; Mutis & Hartmann, 2018; Vozzola et al., 2009). Mutis et al. (2018, p. 137) stated that BIM is ‘a new approach to design, construction, and facility management in which a digital representation of the building process is used to facilitate the exchange and interoperability of information in digital format'. From the existing literature, Ghaffarianhoseini et al. (2017) reflected on the capabilities of BIM applicable at different stages, including model clarification, site coordination, constructability assessment, measurement and estimation, model unifying and clash detection, sequence clarification and information transfer and sharing. In addition to these attributes, Sabet and Chong (2019) claim that the opportunity for safety management provided by BIM can also improve productivity. Therefore, the existing literature shows that there is merit in conducting an in-depth evaluation to obtain a holistic understanding of how effectively the BIM capabilities align with the aspects of project performance. A part of this paper makes the application of BIM more visible from the productivity perspective. The following hypothesis was developed to assess this claim:

H1: BIM has a significant influence on overall project performance.

6.3.2 OSM and project performance.

OSM is an approach in which prefabricated construction components are used at construction sites (Khalfan & Maqsood, 2014). This approach benefits clients in terms of faster and safer construction processes (Arif & Egbu, 2010) and higher sustainability via the '3R concept (reduce, reuse, and recycle)' (Hamid & Kamar, 2012, p. 7). OSM enables clients and contractors to overcome challenges, including schedule disruptions, adverse site conditions and a shortage of skilled labour. The Sustainable Built Environment National Research Centre (2017) asserts that a controlled environment can minimise the likelihood of negative effects arising from sub-optimal material usage and scheduling, safety and quality issues. The minimisation of negative impacts that may lead to rework in construction projects consequently enhances productivity (Hughes &

Thorpe, 2014). OSM provides construction projects with better productivity in comparison with traditional methods of construction (Eastman & Sacks, 2008). Based on the existing relevant literature, Sabet and Chong (2018) have listed the key OSM attributes as automation and series production, faster investment return, more comfortable working conditions, sustainability and safer operations. OSM capabilities and potential benefits have increased its demand, which has been predicted to increase globally. To promote its domestic housing market, Australia should accelerate the implementation of OSM (SBEnrc, 2017). However, criticisms of the applicability of OSM have disrupted these trends (Wynn et al., 2013), and research on how to improve its applicability to guarantee its benefits is warranted. Given that OSM appears capable of enhancing productivity indicators, research that quantifies the efficiency of its capabilities on project performance may enrich the understanding of the applicability of OSM. To contribute to the adoption of OSM in the market, the following hypothesis was developed:

H2: OSM has a significant influence on overall project performance.

6.3.3 OSM–BIM interactions and project performance.

Sabet and Chong (2019) reviewed related works on BIM in OSM (as discussed in section 2.4) and identified 12 potential OSM–BIM interactions that are capable of improving KPrIs, leading to optimal performance. They have called for an empirical study to explore the practicality of these interactions. These potential interactions pertain to site allocation and accessibility, planning and scheduling, safety, sustainability, procurement and contracts, VE, interface management, information flow, sequencing, location management and, last but not least, concurrent engineering. To investigate the relationships between the two approaches that may positively influence these factors and overall project performance, the following hypotheses were developed to be tested via the SEM method:

H3: BIM has a significant influence on OSM.

H4: OSM has a significant influence on OSM–BIM interactions.

H5: BIM has a significant influence on OSM–BIM interactions.

H6: OSM–BIM interactions have a significant influence on overall project performance.

6.4 Research Approach

Figure 6.2 depicts the stages of this research. The first stage involved a literature review on BIM, OSM and BIM in OSM, followed by the identification of research gaps. As discussed in section 3, six hypotheses were developed to evaluate the relationships between latent and observable variables. Table 6.1 displays the constructs as well as the observable variables by which the latent variables could be measured. Observable variables were discussed with several experts and seniors who had a holistic understanding of the two approaches. Their wealth of experience in academia and industry enabled the researcher to identify observable variables, which were used to develop a questionnaire as the data collection tool after ensuring that the capabilities and interactions of OSM and BIM were properly represented. Further, the comprehensibility of the observable variables was tested in a pilot study with ten randomly selected construction practitioners prior to the survey being conducted. SEM was applied for data analysis and consisted of reliability examination and hypothetical tests. Finally, the hypothesis test results determined whether the hypothetical model was confirmed or needed revision.

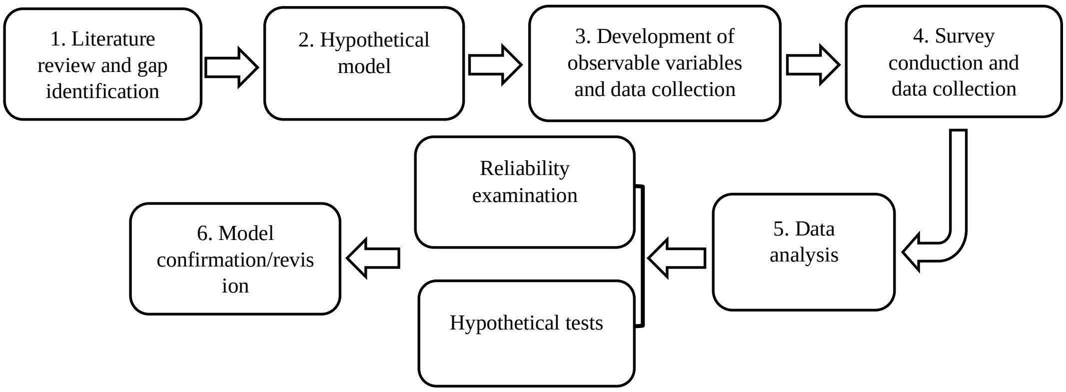

Figure 6.2. Flowchart of research stages

Table 6.1 *SEM measurements*

Latent variable	Abbrev.	Capabilities/ interactions	Observable variables/indicators	Sources contributing to development of indicators
BIM	3D	3D modelling	A detailed virtual BIM offers spatial, executive and material specifications	Azhar, 2011
	CA	Constructability assessment	Visualisation of construction considerations or variation assessment before construction commencement results in cost and time efficiency	Fadoul et al., 2017
	ME	Measurement/estimation	BIM offers accurate quantity of materials and estimation of their total cost	Wu et al., 2014
	CD	Clash detection	BIM detects conflict and interference by combining the 3D designs of structure, architecture and installation	Wang et al., 2016
	SC	Sequence clarification	Possibility of linking planning and scheduling via supportive software such as Navisworks in a BIM package clarifies project sequence	Lee et al., 2015
	SMB	Safety management	Virtual site space and automated available	Martinez-Aires et al.,

Latent variable	Abbrev.	Capabilities/ interactions	Observable variables/indicators	Sources contributing to development of indicators
			safety measurements provided by BIM support safety management at construction sites	2018; Zhang et al., 2013
	PS	Planning and scheduling	Possibility to link planning and scheduling via supportive software in BIM packages such as Navisworks limits deviations and ensures progress	Kiani et al., 2015
	SC	Site coordination	A virtual space results in optimisation of construction activity congestion and site allocation	Azhar, 2011
OSM	AP	Automation and series production	Centralisation of construction activities and series production through automation in a factory environment may reduce activity congestion at the construction site	Eastman & Sacks, 2008; Tibaut et al., 2016
	SM	Safety management	A centralised control environment is safer in OSM-based projects	Pan et al., 2012; SBEnrc, 2017
	ST	Sustainability	Material and energy usage are more controllable (less waste) in the factory environment	Boyd et al., 2013
	FR	Faster investment return	OSM helps shorten project completion time	Elnaas et al., 2009
	WC	Working conditions	Labour costs are cheaper and working conditions more comfortable in factory environments compared with construction sites	Zhai, Reed, & Mills, 2014
	MKT	Marketing	Availability of various volumetric shapes of	Eastman & Sacks, 2008

Latent variable	Abbrev.	Capabilities/ interactions	Observable variables/indicators	Sources contributing to development of indicators
			prefabricated elements better support project progress via OSM compared with traditional construction	
OSM–BIM	I1SLM1	Sequence and location management	BIM has the ability to plan and link the three processes of design, production and positioning of OSM components	Sabet & Chong, 2018; Santos et al., 2019
	I1SLM2		BIM enables the best components to be stocked for later dispatch by offering a 3D site space	Babič, Podbreznik, & Rebolj, 2010
	I1SLM3		Component dispatching is more organised in a virtual site space in OSM–BIM-based projects	
	I2,3PS1	Planning and scheduling	BIM supports manufacturers by addressing the exact specifications of components, minimising errors affecting project progress	Utiome & Drogemuller, 2013
	I2,3PS2		BIM's information sharing and communication enables early planning and scheduling for logistical issue of manufactured components in urban sites for component transfer through timely decision-making	Bortolini, Formoso, & Viana, 2019
	I4SM1	Safety management	BIM enables safer movement and transfer of prefabricated components by providing shop drawings of crane	Yeoh, Wong, & Peng, 2016

Latent variable	Abbrev.	Capabilities/ interactions	Observable variables/indicators	Sources contributing to development of indicators
			operations on lifting and moving loads and virtual accessibility of the relevant area	
	I4SM2		Virtual site accessibility enables safer component dispatch (best route for transferring) because potentials for collision are identified	Shang & Shen, 2016
	I4SM3		BIM recognises potential falls in OSM-based projects because manufactured units may be large and heavy	Zhang et al., 2015
	I5,6,7ST1	Sustainability	Professional comfort is achieved via effective communication in OSM–BIM projects	Abanda et al., 2017; Juszczyk et al., 2015
	I5,6,7ST2		BIM can reduce or minimise waste by providing accurate amounts of construction materials in OSM–BIM projects	Liu et al., 2011
	I8IM1	Interface management	BIM transfers paper-based drawings of prefabricated components to a 3D model that offers quick access to information for stakeholders	Nath et al., 2015
	I8IM2		Required changes to component manufacture may be quickly managed among stakeholders and actioned through BIM's information-sharing platform	Woo, 2006
	I9CC1	Contract condition	In OSM–BIM projects, the responsibility for mistakes or failure of	Chao-Duivis, 2011; Luth et al., 2014

Latent variable	Abbrev.	Capabilities/ interactions	Observable variables/indicators	Sources contributing to development of indicators
			contractual obligations is easily identified	
	I9CC2		Appropriate BIM contractual arrangements in an OSM-based project may prevent potential disputes	Fan et al., 2019
	I10IT1	Information technology	BIM promotes OSM by identifying repetition, resulting in mass production in manufacture	Sabet & Chong, 2019
	I10IT2		Building regulations may be checked in BIM models, and manufacturers may be notified of failure in design before the commencement of physical work	Sabet & Chong, 2019
	I10IT3		BIM via 3D modelling (greater visualisation) enables manufacturer to better manage information and realise the required specifications of ordered parts	Tahir et al., 2018; Martinez et al., 2019
	I11VE1	Value engineering	BIM enables the systematic use of OSM, increasing predictability, constructability and efficiency and adding value to projects	Jrade & Lessard, 2015; Abanda et al., 2017
	I11VE2		The capability of visualisation in BIM better enables cost optimisation by revealing the exact quantity of alternative materials	Yin et al., 2019; Gbadamosi et al., 2018
	I12CE	Concurrent engineering	Opportunities of fast-tracking and conducting activities in parallel is better supported in an OSM–BIM-based	Farnsworth et al., 2015; Sabet & Chong, 2019

Latent variable	Abbrev.	Capabilities/ interactions	Observable variables/indicators	Sources contributing to development of indicators
			project, reflecting the objectives of concurrent engineering	
Project performance		Quality	BIM–OSM interactions improve project	Lee & Kim, 2017
		Cost	BIM–OSM interactions reduce project costs	Ocheoha & Moselhi, 2018
		Time	BIM–OSM interactions shorten project duration	Arashpour et al., 2018
		Safety	BIM–OSM interactions improve project	Abanda et al., 2017
	STS	Stockholder satisfaction	BIM–OSM interactions improve stakeholder relationships and satisfaction	Abanda et al., 2017

6.5 Data Analysis and Findings

6.5.1 Data collection.

Australia was selected as the location of this research study. Construction practitioners with relevant expertise were provided with a Qualtrics survey link. Paper questionnaires were also distributed. The construction board of Engineers Australia, social media (LinkedIn) and construction companies were contacted to network with respondents. Respondents included construction managers, supervisors, project engineers, site engineers, quantity surveyors and architects with academic or professional experience of BIM and OSM. In total, 687 questionnaires were distributed, 77 of which were considered sufficiently valid to be included in the data analysis. A low response rate is common in studies investigating the adoption of emerging techniques and innovations in the construction industry (Ahankoob, Manley, Hon, & Drogemuller, 2018). An Australian research study by Ahankoob et al. (2018) focusing on BIM and the learning capacity of contractors was based on only 57 valid responses (12% response rate). Ling (2003) conducted a survey on innovations in the construction field, obtaining a response rate of only 6%. An effective method of motivating professionals to participate is to contact a representative (i.e. one who represents a number of practitioners) of institutions and companies. Representatives responded to the questionnaire based on what they had observed in projects and following careful reviews of project reports, contributing to the sufficiency and validity of the data.

Observable variables were evaluated by the respondents based on a 5-point Likert scale. SEM was applied to analyse the respondents' answers. As SEM requires significant data, bootstrapping was also applied to increase the accuracy of the data analysis.

6.5.2 Reliability of constructs.

Evaluation of the consistency and accuracy of the research instrument. An instrument is considered accurate if it measures what it is intended to measure and reliable if it produces the same results under the same conditions (Bolarinwa, 2015). Cronbach's alpha (with a coefficient of > 0.7) was used to evaluate the reliability of the scales (Santos, 1999). Cronbach's alpha for the questionnaire (0.94, as shown in Table 6.2) confirms its reliability.

Table 6.2 *Reliability statistics*

Cronbach's alpha	Cronbach's alpha based on standardised items	No. of items
0.941	0.942	38

Table 6.3 shows the factor loadings that represent an acceptable correlation coefficient (> 0.3) for each observed variable. In other words, each variables appropriately contributed to the suitability of questionnaire to measure what was intended to be measured.

Table 6.3 *Measurement scale and properties of constructs*

Construct		Observed variable (abbrev.)	Correlation coefficient (factor loading)	Cronbach's alpha if item deleted
BIM		3D	0.46	0.94
		CA	0.54	0.94
		ME	0.54	0.94
		CD	0.35	0.94
		SC	0.53	0.94
		SMB	0.61	0.94
		PS	0.45	0.94
OSM		SC	0.48	0.94
		AP	0.48	0.94
		SMO	0.48	0.94
		STO	0.38	0.94
		FR	0.36	0.94
		WC	0.39	0.94
		MKT	0.48	0.94
Interactions	I1	SLM1	0.32	0.94
		SLM2	0.58	0.94
		SLM3	0.60	0.94
	I2,3	PS1	0.46	0.94
		PS2	0.58	0.94
	I4	SM1	0.60	0.94
		SM2	0.61	0.94
		SM3	0.68	0.94
	I5,6,7	ST1	0.49	0.94
		ST2	0.76	0.94
	I8	IM1	0.60	0.94
	I9	CC1	0.65	0.94
		CC2	0.46	0.94
	I10	IT1	0.60	0.94
		IT2	0.38	0.94
		IT3	0.57	0.94
	I11	VE1	0.47	0.94
		VE2	0.46	0.94
	I12	CE	0.61	0.94
Project performance		Time	0.53	0.94
		Cost	0.62	0.94
		Quality	0.68	0.94

Construct	Observed variable (abbrev.)	Correlation coefficient (factor loading)	Cronbach's alpha if item deleted
	Safety	0.65	0.94
	Satisfaction	0.54	0.94

6.5.3 Hypothesis testing and interpretation.

SEM supported by bootstrapping was used to test the hypotheses. Standardised path coefficient β was obtained from SEM using AMOS software. As Table 6.4 shows, the p-values of the two first paths were greater than 0.05. This implies that, individually, BIM and OSM did not significantly influence overall project performance. Therefore, H1 and H2 are rejected. As can be seen in the third row, BIM significantly influenced OSM was detected ($\beta = 0.4$, $p < 0.05$). Therefore, H3 is supported. Moreover, there was a significant influence from both OSM ($\beta = 0.79$, $p < 0.05$) and BIM ($\beta = 0.40$, $p < 0.05$) on the interactions between OSM and BIM. This implies that each approach is capable of interacting with the other. Therefore, H4 and H5 are supported. Finally, the interaction between OSM and BIM significantly influenced overall project performance ($\beta = 0.86$, $p < 0.05$). In the other words, the capabilities of each approach resulted in constructive OSM–BIM interactions, improving the KPrIs contributing to the expected project performance. Thus, H6 is supported.

Table 6.4 *Hypothesis test results*

Hypothesis	Path	Path coefficient (β)	*p*-value	Interpretation
H1	Project performance < BIM	0.00	0.279	Not supported
H2	Project performance < OSM	0.49	0.175	Not supported
H3	OSM < BIM	0.31	0.003	Supported
H4	OSM–BIM interactions < OSM	0.79	0.015	Supported

H5	OSM–BIM interactions < BIM	0.40	0.009	Supported
H6	Project performance < OSM–BIM interactions	0.86	0.000	Supported

Figure 6.3 shows the path coefficients (regression weights) of the capabilities of each approach and the interaction between OSM and BIM. For example, 3D BIM had a weight of 0.68, OSM automation and series production had a weight of 1 and concurrent engineering (I12CE) had a weight of 0.72. Based on these findings, OSM–BIM interactions played a mediating role between BIM and OSM techniques in the structural model of this research.

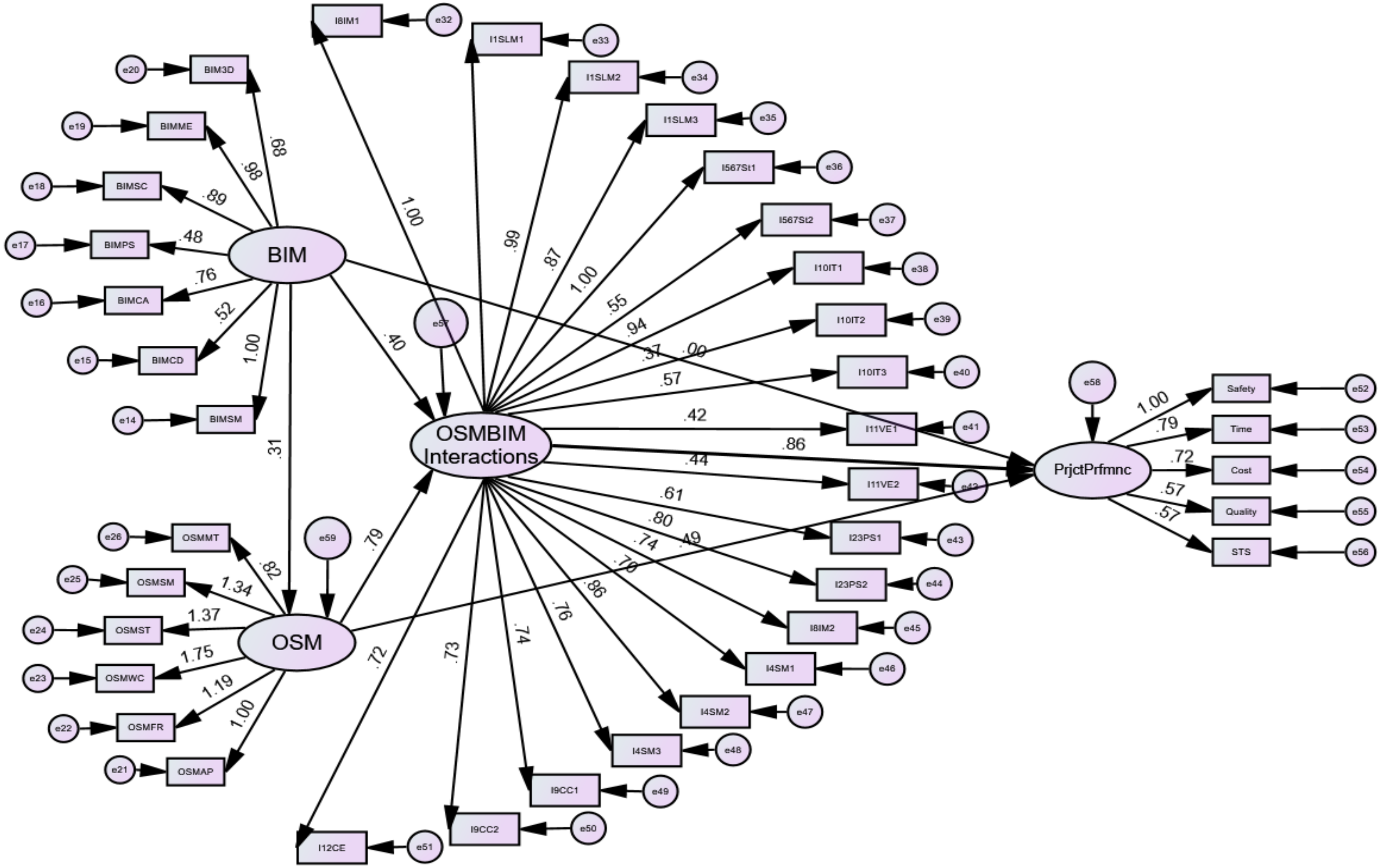

Figure 6.3. SEM model

6.6 Discussion and Contributions

Existing literature on BIM in OSM is limited. Goulding et al. (2012) claimed that BIM can resolve fragmentation among designers, contractors, and manufacturers. Through a qualitative research study, Vernikos et al. (2013) discovered that a OSM–BIM system provides opportunities to improve interface management and configuration, access information, and optimize procurement .They also claimed that it facilitates better project contracts and more constructive managerial measures. Nawari et al. (2012) established that a manufacturer—as a party in a project—could benefit from extracting sufficient data from a BIM model. Ezcan et al. (2013) claimed that an enriched BIM model can cover the weaknesses in an OSM-based project. Amanda et al. (2017) reported that BIM in OSM-based projects provided more beneficial opportunities than traditional construction projects. In addition, Liu et al. (2019) highlighted a range of gaps, including the lack of a BIM generative system in OSM-based investigation. A BIM-based system of design assessment and optimisation is necessary for linking the design and assembly stages of a project (Ghadamosi et al., 2019). Ghadamosi et al. (2019) integrated "the principles of Design for Manufacture and Assembly (DFMA) and Lean Construction" (p. 1) to develop a BIM-based system.

This research measured the practicality of the individual capabilities of BIM and OSM techniques and the practicality of their combined capabilities referred to OSM-BIM interactions. To achieve this, SEM was used as a comprehensive method for clarifying potential sophisticated relationships among the interconnected variables of this study. A measurement instrument was developed to quantify the practicality of the two techniques' capabilities. Additionally, the measurement instrument provided respondents with an opportunity to evaluate the capabilities of the techniques against their potential interactions. In other words, the respondents were provided with full descriptions of capabilities and interactions to inform their judgment.

The first theoretical contribution is that interactions between OSM and BIM act as mediators to improve KPrIs, which leads to overall project performance. This shows that, when both approaches are systematically adopted, their capabilities reinforce each other. These interactions have been addressed on how and which stages to be applied throughout a project. Therefore, the interactions identified in this study have practical implications for planning and management. For example, an enriched BIM model clarifies any required technical specifications for building components with high accuracy (Azhar, 2011). These specifications limit the chance of construction errors. Meanwhile, OSM offers automation and series production, which significantly contribute to a faster flow of progress (Eastman & Sacks, 2008; Tibaut et al., 2016). This system has been identified as a capable solution to improve the affordability of end users (Mostafa & Chileshe, 2018). In Australia, OSM adoption is one of the pathways for construction industry improvement (Hu& Chong, 2019) and the role of manufacturers contributing to an integrated project team has been highlighted (Hu& Heap, 2020). Therefore, an OSM–BIM system can provide a construction project with accurate technical specifications to accelerate the construction process. This is vital to project performance in series production because rectifying errors in manufactured components takes time and costs money, which can hinder projects. In an OSM–BIM-based project, these capabilities can support interface management and satisfy stakeholders. The interactions can also be clarified in terms of concurrent engineering, which refers to fast-tracking the review and confirmation of the executive technical requirements. This fast-tracking is made possible by developing virtual architectural, structural, electrical, and mechanical models, rather than sequentially evaluating paper-based models. Therefore, the objective of concurrent engineering is fulfilled by the opportunity of doing jobs in parallel (Farnsworth et al., 2015).

Innovation and the diffusion of innovation are the only ways to address future demand in the construction industry (Lindblad & Guerrero, 2020). This research was grounded in an interactive perspective, since it clarified three essential elements of innovation: idea generation, opportunities, and diffusion (Gambatese et al., 2011). "Diffusion," as defined by Kale and Arditi (2010), is "the process by which an innovation is communicated through certain channels over time among the members of a social system" (p. 330). The concurrent application of OSM and BIM, in a hybrid system, could allow the identified interactions to fulfil the objectives of both techniques. For these reasons, the hybrid system represents an innovative process for overall project performance, which can be widely applied in the industry. This application is in line with diffusion innovation theory.

6.7 Conclusion

Both OSM and BIM have been identified as revolutionary techniques, capable of addressing the issues threatening construction productivity. However, the uptake of OSM and BIM varies from country to country. Gelic et al. (2016) highlighted Australia's limited uptake of BIM (Gelic et al. 2016) and Hosseini et al. (2018) argued for the necessity of accelerating BIM's maturity in Australia. Additionally, the extremely limited success of OSM (Duc et al., 2014) and the lack of systematic progress from on-site construction to OSM mean that the growth rate of OSM is lagging in comparison with adoption trends in other pioneer countries that practice OSM (Khalfan & Maqsood, 2014). The uncertain status of BIM may originate from its limited uptake in Australia (Gelic et al., 2016) and its consequent immaturity in much of the Australian market (Hosseini et al., 2018). These issues may impede the effectiveness of the individual application of the techniques and prevent BIM in OSM from moving beyond infancy in Australia.

This research study developed hypotheses and evaluated the relationships between BIM, OSM, OSM–BIM interactions and overall project performance. To analyse the data and test the hypotheses, SEM was used, supported by bootstrapping. As a professional format of SEM, a hypothetical model and null hypotheses were developed. Regression and correlation tests were applied to evaluate the hypotheses. A range of coefficients were used to interpret the results. The findings show that there was no significant influences from BIM and OSM on overall project performance when these techniques were applied individually. Moreover, a significant influence from BIM on OSM was found, meaning that the capabilities of the two techniques were interactive. Thus, a significant influence from OSM–BIM interactions on overall project performance was hypothesised and supported. By systematically adopting these techniques, interactions are capable of boosting project performance via improving KPrIs. The current study revealed the degree of the influence (regression weight) of each capability as well as direct and indirect influences of the techniques on overall project performance (see Figure 6. 3). A systematic adoption of these techniques has been addressed by developing their interactions. These interactions are capable of optimizing dimensions of project performance, namely time, cost, quality, safety, and stockholders' satisfaction, by improving KPrIs. As has been highlighted, productivity improvement is followed by project performance.

Therefore, the output of this research may encourage clients and stakeholders to embrace hybrid OSM–BIM-based projects to boost overall project performance. Interactions should be implemented in the planning and managerial stages to boost overall performance in the architecture, engineering and construction industry.

Nevertheless, certain limitations need to be considered in this research. In this study, the construction practitioners made professional judgments according to the current statuses of OSM and BIM in Australia. Therefore, the conclusions of this research cannot be generalised to other countries as a consequence of the small sample sizes and subsequently limited data. However, some respondents represented a larger number of respondents as they were the representatives of a company. Further research is needed to reinforce the findings of these studies so that the construction industry would not resistant the adoption of the hybrid OSM–BIM system.

Chapter 7: Research Contributions

7.1 Introduction

This research study includes four articles, comprising Chapters 2 to 5. The findings and contributions of each article have been discussed at the end of each chapter. This chapter concludes the aim of the research, summarises how the objectives were satisfied, flags the limitations and recommends further research.

7.2 The Satisfaction of Research Objectives and Research Contributions

7.2.1 To identify productivity fundamentals and highlight the role of advanced techniques for productivity improvement

The decline of construction productivity, which resulted in poorer project performance, forced authorities to seek the root of this reduced productivity. The reinvention of construction was deemed essential and the implementation of advanced techniques has been observed as one of the solutions. However, it is clear that the advanced techniques may not cover all the factors in productivity. Therefore, the first step was to develop a range of productivity fundamentals. To pursue this objective, 128 academic publications were analysed. This objective was satisfied by developing six measures at the concept and design levels, four measures at the contract and procurement steps and four measures at the execution stage. Following this, the pathway through which the commonly advanced techniques influenced the aspects of project performance at the pre-construction and construction stages was clarified. From there, construction professionals could understand how to optimise time, cost, quality, safety and stakeholder satisfaction. Additionally, it is implicit that these advanced techniques could be reinforced by productivity fundamentals. In other words, the influences of the implementation of advanced techniques could be maximised by the company incorporating productivity fundamentals. This plan of study could also enable technique developers to conceptualise the requirements of more influential techniques in the future.

7.2.2 To investigate the current influential standalone capabilities of BIM and OSM for a hybrid OSM–BIM conceptual framework

New concepts, such as OSM and BIM, have been revolutionary movements in the construction industry. However, these methods have not yet fulfilled their full potential in practice. These techniques could be independently applied in construction projects, but their integrated application may contribute to the fulfilment of their full potential and true benefits in the industry. Hence, a conceptual framework was required to address a hybrid OSM–BIM system (HOBS). This objective has been satisfied through a holistic understanding of the standalone capabilities of the two techniques. A Scoping review was applied, and 47 academic publications were analysed to contribute to the achievement of this objective. This research argued that BIM might effectively improve OSM and that a range of potential interactions could be applied at the design and construction stages. These potential interactions must be systematically adopted by a collaboration of participants. From that informative discussion and overview, the idea of BIM in OSM was well-formulated to bridge the capabilities of OSM and BIM. This study provided a foundation for the development of the potential technical interactions applicable in planning and managerial schemes. Overall, a well-formulated idea of BIM in OSM, as well as a direction for further research, is the contribution of this effort.

7.2.3 To identify the potential interactions of BIM and OSM for improving productivity

From a productivity perspective, KPrIs need to be improved for overall project performance. These KPrIs have been targeted by the capabilities of advanced techniques. The objectives set out in BIM and OSM have been theoretically achieved, but an argument has been made that the results may differ once they come into practice. In other words, the existing relevant literature implies that the BIM and OSM capabilities may influence a range of KPrIs that result in better project performance. However, these objectives have not yet been fulfilled in practice. A hybrid concept was raised, pairing BIM with OSM for overall project performance. BIM has been hypothesised as having the potential to link design, manufacturing and construction. Therefore, the first step was an in-depth investigation to identify the KPrIs. Second, the development of potential interactions was required. Third, at which stage and how these OSM–BIM interactions influence KPrIs was discussed. This objective was satisfied by scanning 100 academic publications. A conceptual figure of KPrIs was generated and 12 systematically discovered OSM–BIM interactions were the output. This research contributes to the body of knowledge concerning BIM in OSM by clarifying the pathways of how potential OSM–BIM interactions influence KPrIs. The results of these investigations can improve the planning and managerial stages, enabling productivity improvement in OSM-based projects.

7.2.4 To determine the influences of the standalone capabilities of OSM and BIM, as well as their interactions in project performance

The high demand for improvements in construction productivity has led to the emergence of advanced techniques. These advanced techniques have been supposed to optimise project performance via the improvement of KPrIs. It has been suggested that the concurrent application of BIM and OSM, rather than the individual application of these techniques, could enhance project performance. The research scope in this study extended to Australia. The main output of this research revealed significant influences from OSM–BIM interactions on overall project performance. This shows that by systematically adopting both techniques, their capabilities can reinforce each other. These interactions were technically addressed where they were applicable. The second theoretical contribution of this research is the diffusion of innovation theory because the identified interactions support the concurrent adoption of OSM and BIM. These interactions fulfil the objectives of both techniques in functional hybrid OSM–BIM systems, which may be widely implemented in the construction industry.

These practical implications are notable because the applicability of interactions in projects can be prescribed. Therefore, they can be a practical reference for the practitioner in the planning and construction stages.

7.3 Overall Research Contributions

Apart from the four above-mentioned contributions, this research has uncovered a range of constructive interactions that contribute to diffusion theories. The theories and practices that paved the way for modern construction did so because they presented strategic improvements to industry performance levels. The diffusion and implementation of sustainable, modern construction practices require that technique developers, policy makers and stakeholders share an innovative and interactive perspective (the role of clients is disputed) (Gambatese & Hallowell, 2011; Zhang et al., 2020). Holding this point of view to ‘influence the speed and direction of techniques development and diffusion’ (Renz & Solas, 2016, p. 44) has been on the agenda at government forums in both developing and developed countries. This research was grounded in the interactive point of view, since it clarified three essential elements of innovation: idea generation, opportunities and diffusion (Gambatese et al., 2011). ‘Diffusion’, as defined by Kale and Arditi (2010), is ‘the process by which an innovation is communicated through certain channels over time among the members of a social system’ (p. 330). Innovation and its diffusion are the only ways to address future demand in the construction industry (Lindblad & Guerrero, 2020). For these reasons, the hybrid OSM–BIM system represents an innovative process for overall project performance, which can be widely applied in the industry. This application is in line with the diffusion innovation theory.

7.4 Conclusion

The construction industry has always suffered from poor productivity. Construction productivity underlies project performance and, consequently, projects have lagged below the expected level of performance. Advanced techniques have emerged to address this issue, but they may not cover all the required areas of construction productivity. More supportive fundamentals could reinforce the advanced techniques for project performance. The concurrent application of some of these techniques may generate constructive interactions that result in better overall project performance. BIM and OSM, as advanced techniques, were bridged to eliminate poor construction productivity and to enable overall project performance. This research aimed to determine the influences of OSM–BIM interactions on overall project performance. In this regard, first, an in-depth investigation was required to identify the causes of poor productivity and the attempted solutions. To identify the required productivity fundamentals and scan the advanced techniques and how they influenced project performance, 128 academic publications were reviewed. By integrating these findings, a conceptual framework was developed.

This research then focused on OSM and BIM techniques for a holistic understanding of the two techniques. The idea of BIM in OSM was conceptualised by a hybrid OSM–BIM framework, through the consultation of 47 academic papers. A conceptual figure of key productivity indicators was developed to contribute to the discussion on how the hybrid OSM–BIM system could improve construction productivity. Twelve potential interactions between OSM and BIM were the key output of this effort, supported by 100 academic articles. The influences of OSM–BIM interactions on overall project performance were empirically investigated through a data collection from survey and data analysis via SEM (using AMOS software). The findings showed that there were no significant influences from BIM and OSM on overall project performance when these techniques were applied individually. Moreover, a significant influence from BIM on OSM was found, meaning that the capabilities of the two techniques were interactive. Thus, a significant influence from OSM–BIM interactions on overall project performance was revealed.

7.5 Limitations, Recommendations and Future Research Directions

This research can be considered to have certain limitations. One is the lack of projects within which both techniques were fully applied. The report detailing OSM–BIM-based projects could represent a significant benchmark in theory and effectively support the critical evaluation of the concept. The second limitation is the lack of professionals who either had experience, or were academically familiar, with the two techniques. The third is the lack of interest among the contractors and clients who were approached for this study. The last limitation is the small data sample. In this study, the construction practitioners made professional judgments according to the current statuses of OSM and BIM in Australia. As data sample was small, the conclusions of this research cannot be generalised to other countries.

Hence, the value of a hybrid OSM–BIM system should be brought to the attention of companies, to facilitate a more collaborative environment for this innovative research. Research discussing BIM in OSM is limited, but further research could leverage the benefit of the hybrid system described in this study.

The construction industry has been resistant to the systematic adoption of new and advanced techniques, such as BIM and OSM, to fully enable their capabilities and their interactions. This means that the partial application of these techniques may interrupt their effectiveness.

Further studies from different perspectives may reveal the effectiveness of the concurrent application of OSM and BIM. The perspective of a smart city could be one viewpoint that accelerates the adoption of a hybrid OSM–BIM system in the construction industry, which is resistant to change. This OSM–BIM system could be referred to as smart construction. A smart city is regarded as a system with interconnected sub-systems with complex social–economic interconnections. The construction industry is one sub-system that plays a critical role in the global economy. Modernised construction is recognised as a significant contributor to smart city development. A modernised construction industry that offers more efficient services to society’s users is also an inevitable part of delivering essential services and contributing to quality of life. From a smart city perspective, OSM–BIM interactions could contribute to the criteria of smart cities. In other words, the interactions can be found in the objectives of sustainability and efficiency as the main themes of smart city development. According to Albino et al. (2015) and Shapiro et al. (2006), the criteria of the smart city can be divided into six categories. Figure 6.1 shows the categories that the idea of smart construction can contain. A prospective study in this area, aligned with the diffusion of innovation theory, could contribute to the field by promoting an integrative industry viewpoint.

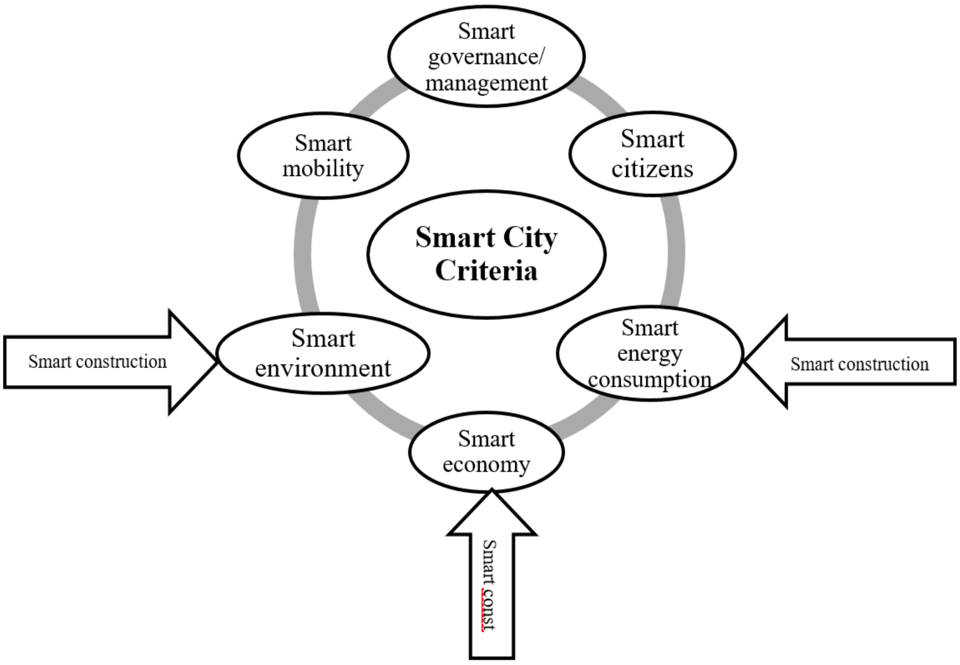

Fig 7.1. Conceptual framework of smart construction for a smart city

7.6 Summary

This hybrid thesis included four academic papers, comprising Chapters 2 to 5, as the foundations of its research. This chapter briefly reflected on these foundations, articulating the research contributions, limitations, recommendations and future research directions.

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Appendix A

Table A.1

Measurement of key constructs

Latent variable	Abbrev.	Capabilities/ interactions	Observable variables/indicators	Sources contributing to development of indicators
Building information modelling (BIM)	3D	3D modelling	A detailed virtual BIM offers spatial, executive and material specifications	Azhar, 2011
	CA	Constructability assessment	Visualisation of construction considerations or variation assessment before construction commencement results in cost and time efficiency	Fadoul et al., 2017
	ME	Measurement/estimation	BIM offers accurate quantity of materials and estimation of their total cost	Wu et al., 2014
	CD	Clash detection	BIM detects conflict and interference by combining the 3D designs of structure, architecture and installation	Wang et al., 2016
	SC	Sequence clarification	Possibility of linking planning and scheduling via supportive software such as Navisworks in a BIM package	Lee et al., 2015

Latent variable	Abbrev.	Capabilities/ interactions	Observable variables/indicators	Sources contributing to development of indicators
			clarifies project sequence	
	SMB	Safety management	Virtual site space and automated available safety measurements provided by BIM support safety management at construction sites	Martinez-Aires et al., 2018; Zhang et al., 2013
	PS	Planning and scheduling	Possibility to link planning and scheduling via supportive software in BIM packages such as Navisworks limits deviations and ensures progress	Kiani et al., 2015
	SC	Site coordination	A virtual space results in optimisation of construction activity congestion and site allocation	Azhar, 2011
Off-site manufacturing (OSM)	AP	Automation and series production	Centralisation of construction activities and series production through automation in a factory environment may reduce activity congestion at the construction site	Eastman & Sacks, 2008; Tibaut et al., 2016
	SMO	Safety management	A centralised control environment is	Pan et al., 2012; SBEnrc, 2017

Latent variable	Abbrev.	Capabilities/ interactions	Observable variables/indicators	Sources contributing to development of indicators
			safer in OSM-based projects	
	STO	Sustainability	Material and energy usage are more controllable (less waste) in the factory environment	Boyd et al., 2013
	FR	Faster investment return	OSM helps shorten project completion time	Elnaas et al., 2009
	WC	Working conditions	Labour costs are cheaper and working conditions more comfortable in factory environments compared with construction sites	Zhai, Reed, & Mills, 2014
	MKT	Marketing	Availability of various volumetric shapes of prefabricated elements better support project progress via OSM compared with traditional construction	Eastman & Sacks, 2008
OSM–BIM	I1SLM1	Sequence and location management	BIM has the ability to plan and link the three processes of design, production and positioning of OSM components	Sabet & Chong, 2018; Santos et al., 2019
	I1SLM2		BIM enables the best components to be stocked for	Babič, Podbreznik,

Latent variable	Abbrev.	Capabilities/ interactions	Observable variables/indicators	Sources contributing to development of indicators
			later dispatch by offering a 3D site space	& Rebolj, 2010
	I1SLM3		Component dispatching is more organised in a virtual site space in OSM–BIM-based projects	
	I2,3PS1	Planning and scheduling	BIM supports manufacturers by addressing the exact specifications of components, minimising errors affecting project progress	Utiome & Drogemuller, 2013
	I2,3PS2		BIM's information sharing and communication enables early planning and scheduling for logistical issue of manufactured components in urban sites for component transfer through timely decision-making	Bortolini, Formoso, & Viana, 2019
	I4SM1	Safety management	BIM enables safer movement and transfer of prefabricated components by providing shop drawings of crane operations on	Yeoh, Wong, & Peng, 2016

Latent variable	Abbrev.	Capabilities/ interactions	Observable variables/indicators	Sources contributing to development of indicators
			lifting and moving loads and virtual accessibility of the relevant area	
	I4SM2		Virtual site accessibility enables safer component dispatch (best route for transferring) because potentials for collision are identified	Shang & Shen, 2016
	I4SM3		BIM recognises potential falls in OSM-based projects because manufactured units may be large and heavy	Zhang et al., 2015
	I5,6,7ST 1	Sustainability	Professional comfort is achieved via effective communication in OSM–BIM projects	Abanda et al., 2017; Juszczyk et al., 2015
	I5,6,7ST 2		BIM can reduce or minimise waste by providing accurate amounts of construction materials in OSM–BIM projects	Liu et al., 2011
	I8IM1	Interface management	BIM transfers paper-based drawings of prefabricated	Nath et al., 2015

Latent variable	Abbrev.	Capabilities/ interactions	Observable variables/indicators	Sources contributing to development of indicators
			components to a 3D model that offers quick access to information for stakeholders	
	I8IM2		Required changes to component manufacture may be quickly managed among stakeholders and actioned through BIM's information-sharing platform	Woo, 2006
	I9CC1	Contract condition	In OSM–BIM projects, the responsibility for mistakes or failure of contractual obligations is easily identified	Chao-Duivis, 2011; Luth et al., 2014
	I9CC2		Appropriate BIM contractual arrangements in an OSM-based project may prevent potential disputes	Fan et al., 2019
	I10IT1	Information technology	BIM promotes OSM by identifying repetition, resulting in mass production in manufacture	Sabet & Chong, 2019
	I10IT2		Building regulations may be checked in	Sabet & Chong, 2019

Latent variable	Abbrev.	Capabilities/ interactions	Observable variables/indicators	Sources contributing to development of indicators
			BIM models, and manufacturers may be notified of failure in design before the commencement of physical work	
	I10IT3		BIM via 3D modelling (greater visualisation) enables manufacturer to better manage information and realise the required specifications of ordered parts	Tahir et al., 2018; Martinez et al., 2019
	I11VE1	Value engineering	BIM enables the systematic use of OSM, increasing predictability, constructability and efficiency and adding value to projects	Jrade & Lessard, 2015; Abanda et al., 2017
	I11VE2		The capability of visualisation in BIM better enables cost optimisation by revealing the exact quantity of alternative materials	Yin et al., 2019; Gbadamosi et al., 2018
	I12CE	Concurrent engineering	Opportunities of fast-tracking and conducting activities in parallel is better supported in an	Farnsworth et al., 2015; Sabet & Chong, 2019

Latent variable	Abbrev.	Capabilities/ interactions	Observable variables/indicators	Sources contributing to development of indicators
			OSM–BIM-based project, reflecting the objectives of concurrent engineering	
Project performance		Quality	BIM–OSM interactions improve project	Lee & Kim, 2017
		Cost	BIM–OSM interactions reduce project costs	Ocheoha & Moselhi, 2018
		Time	BIM–OSM interactions shorten project duration	Arashpour et al., 2018
		Safety	BIM–OSM interactions improve project	Abanda et al., 2017
	STS	Stockholder satisfaction	BIM–OSM interactions improve stakeholder relationships and satisfaction	Abanda et al., 2017

Appendix B

Permission from the *Journal of Advances in Civil Engineering (Hindawi publications)*

From: Rennuel Gil Caguicla <help@hindawi.com>
Sent: Tuesday, 7 April 2020 11:43 AM
To: Pejman Ghasemi Poor Sabet <pejman.ghasemip@postgrad.curtin.edu.au>
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Please let me know if I can assist you with anything else.

Best regards,

Rennuel

Appendix C

Permission from the *International Journal of Managing Projects in Business (Emerald Publications)*

From: Becky Taylor <btaylor@emerald.com>
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Subject: FW: FW: Request for permission

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I am currently working from home as Emerald’s UK offices are closed in response to the Covid-19 pandemic. Our phone numbers are not being monitored.

Appendix D

Statement of Author’s Contributions

To Whom It May Concern

I, Pejman Ghasemi Poor Sabet, contributed abstract, introduction, poor construction productivity, advanced techniques, review methodology, analysis and findings, discussions, conclusions, recommendations and references significantly to the paper/publication entitled “Pathways for the improvement of construction productivity: A perspective on the adoption of advanced techniques.”

Pejman Ghasemi Poor Sabet

__ ________ (25/06/2020)

I, as a Co-Author, endorse that this level of contribution by the candidate indicated above is appropriate.

Assoc. Prof Heap-Yih Chong

______ [redacted] ______________________ (25/06/2020)

Appendix E

Statement of Author's Contributions

To Whom It May Concern

I, Pejman Ghasemi Poor Sabet, contributed abstract, introduction, the application of BIM and OSM techniques, review methodology, discussion on the formulation of BIM in OSM conclusions and references significantly to the paper entitled "A conceptual hybrid OSM–BIM framework to improve construction project performance."

Pejman Ghasemi Poor Sabet

__ ____________________(25/06/2020)

I, as a Co-Author, endorse that this level of contribution by the candidate indicated above is appropriate.

Assoc. Prof Heap-Yih Chong

____________ [redacted] _______________(25/06/2020)

Appendix F

Statement of Author's Contributions

To Whom It May Concern

I, Pejman Ghasemi Poor Sabet, contributed abstract, introduction, literature review on the key productivity indicators, findings on BIM and OSM for the interactions between them, review methodology, analysis and discussion of the improvements of KPrIs via the the OSM and BIM capabilities and the interactions as well as their influences on the overall project performance, conclusions and references significantly to the paper/publication entitled " Interactions between building information modelling and off-site manufacturing for productivity improvement"

Pejman Ghasemi Poor Sabet

(25/06/2020)

I, as a Co-Author, endorse that this level of contribution by the candidate indicated above is appropriate.

Assoc. Prof Heap-Yih Chong

__________ [redacted] ________________(25/06/2020)

Appendix G

Statement of Author's Contributions

To Whom It May Concern

I, Pejman Ghasemi Poor Sabet, contributed abstract, introduction, literature review, methodology, empirical evaluation the impact of standalone BIM and OSM capabilities and their interactions via KPrIs, SEM application, discussion on overall project performance, conclusions and references significantly to the paper/publication entitled "Appraisal of potential interactions between building information modelling and off-site manufacturing for overall project performance."

Pejman Ghasemi poor Sabet

_ ______________________ (25/06/2020)

I, as a Co-Author, endorse that this level of contribution by the candidate indicated above is appropriate.

Assoc. Prof [redacted]hong

__________ __________________ (25/06/2020)

Dr Chamila Ramanayaka

Appendix H

Dear Sir/Madam,
Welcome to the survey.
You are invited as a construction practitioner to participate in this research. The research aims to discuss how Building Information Modelling (BIM) and Off-site Manufacturing (OSM), as well as their potential interactions, are capable of improving performance/productivity.
The following explanations are provided for respondents to briefly clarify what are BIM and OSM referred to in this research. this survey takes about 15 mins of your time.

The following explanations are provided for respondents to briefly clarify what are BIM and OSM referred to in this research.

- BIM is the process of developing and applying a simulated model of designing, planning, construction and operation of a building. The model contains a collection of digital data and rich information about all details related to a project during its life cycle. The BIM model originated from a smart 3-dimensional CAD which is automatically adaptable to any change and is connected to a shareable database performing as a common source among the parties involved in a project.
- OSM is a modern technique in which off-site constructed components are produced and attached to on-site activities. In fact, the off-site components are produced in a controlling manufacture environment and then transported to and positioned into a construction site.

Your efforts and time are highly appreciable for answering the questionnaire below.

STATEMENT BY PERSON AGREEING TO PARTICIPATE IN THIS STUDY.
I have read the informed consent document and the material contained in it has been explained to me virtually. I understand each part of the document, all my questions have been answered and I freely and voluntarily choose to participate in this study.

○ Yes I consent

○ No I do not consent

Q2.
How do you know BIM?

☐ Only from academic studies

☐ 1-3 years' experience

☐ 3-5 years' experience

☑ Over 5 years' experience

Q3. How do you know OSM?

☐ Only from academic studies

☐ 1-3 years' experience

☐ 3-5 years' experience

☑ Over 5 years' experience

Q4.

Please select an answer for the questions below based on your knowledge and experience in OSM and BIM practices by referring to the scales of Strongly disagree=SD, Disagree=D, Neutral =N, Strongly agree=SA, and Agree=A.

	Strongly agree	Agree	Neither agree nor disagree	Disagree	Strongly disagree
I observe that centralization of the construction activities into a factory environment could reduce activities congestion in construction site that result in a better construction site control .	●	○	○	○	○
I observe that OSM helps in shortening project completion time .	●	○	○	○	○
I observe that a cheaper labour cost in a factory environment compared to the workers payment rate in a construction site .	●	○	○	○	○
I observe that material usage is more controllable (less waste) in the factory environment that results in a better productivity .	●	○	○	○	○
I observe that a centralized controlling environment is safer in OSM-based projects .	●	○	○	○	○
I observe that different and volumetric shapes of the elements can be applied in structural, architectural and installation (mechanical and electrical) designs .	●	○	○	○	○
I observe that a better project progress is achievable through a BIM model that offers accurate quantity of materials and estimation of their total cost .	●	○	○	○	○
I observe that a better project progress is achievable through a BIM model that offers more accurate estimation of their total cost .	●	○	○	○	○
I observe that a higher productivity rate can be resulted by planning software available for a BIM model, such as Naviswork 4D, etc .	○	○	●	○	○
I observe that BIM model limits chance of any deviations during construction stage that improves the project progress.	○	●	○	○	○
I observe that the visualization of construction considerations or variation assessment before actual construction commencement through BIM could result in cost and time efficiency .	○	●	○	○	○
I observe that BIM offers chances to detect any conflict and interference by combining the 3-D designs of structure, architecture, and installations .	○	●	○	○	○

I observe that site coordination through a virtual space results in optimization of construction activities .	○	●	○	○	○
I observe that BIM model has the ability to plan and link the three processes including design, production, and positioning of OSM components .	○	●	○	○	○
I observe that BIM promotes the paper-based drawings of components to a 3-D model that offers all information . This point causes a quicker lead time in OSM-based projects .	○	●	○	○	○
I observe that BIM enables the best components stock for later dispatch via offering a 3D site space or supply -chain management .	○	●	○	○	○
I observe that BIM supports manufacturers by addressing the exact specifications minimizing errors that affect project progress.	○	●	○	○	○
I observe that component dispatching is to be more organized via a virtual site space in an OSM-BIM -based project .	○	●	○	○	○
I observe that BIM's information sharing and communication enables early planning and scheduling for logistics issue of manufactured components in urban sites for components' transfer through timely decision - making (the best date, time and route) .	○	●	○	○	○
I observe that BIM enables safer movement and transfer of the components by providing shop drawings for crane operation on how lifting and moving the loads and virtual accessibility of the relevant area.	○	○	●	○	○
I observe that Virtual site accessibility would enable safer component dispatch (best route for transferring) since any potential of collision would be notified .	●	○	○	○	○
I observe that that BIM would recognize potential falling failures in an OSM-based project since the manufactured unit may be heavy and huge.	○	●	○	○	○
I observe that that BIM can reduce or minimize the waste by providing the accurate amount of the construction material in an OSM-BIM project .	●	○	○	○	○
I observe that a professional comfort is achieved via an effective communication in an OSM-BIM project .	●	○	○	○	○
I observe that any required changes on the component to manufacture would be quickly managed among the stockholders and actioned through BIM's information sharing platform .	●	○	○	○	○

I observe that an appropriate BIM contractual arrangement in an OSM-based project could prevent the potential disputes.	○	●	○	○	○
I observe that in OSM-BIM projects, the responsible side for any mistakes or any failure of contractual obligations are easily identified and traced.	○	●	○	○	○
I observe that BIM promotes OSM via identifying repetition resulting in mass production in manufacture.	○	●	○	○	○
I observe that building regulations could be checked in a BIM model and any failure in design can be notified to manufacturer before commencement any physical works.	○	○	●	○	○
I observe that BIM via 3D model (greater visualization) enables manufacturer to realize the required specifications of the ordered parts.	○	●	○	○	○
I observe that BIM enables a systematic use of OSM and increases predictability and constructability, and efficiency that result in adding value on the project.	○	●	○	○	○
I observe that the capability of visualization in BIM better enables cost optimization through revealing the exact quantity of the alternative materials.	○	●	○	○	○
I observe that the opportunities of fast-tracking and doing some activities in parallel would be better supported in an OSM-BIM-based projects that reflect the objectives of concurrent engineering.	●	○	○	○	○
I observe that the BIM and OSM interactions have improved the quality of the project.	○	●	○	○	○
I observe that the outcome of the BIM and OSM interactions have reduced the cost of the project.	○	●	○	○	○
I observe that the BIM and OSM interactions have shortened the duration of the project.	●	○	○	○	○
I observe that the BIM and OSM interactions have improved the safety aspects of the project.	●	○	○	○	○
I observe that the BIM and OSM interactions have improved stakeholders' relationship and satisfaction toward a perfect project progress.	○	●	○	○	○

Q6. You are very welcomed to recommend any other potential interaction that can be developed among OSM and BIM and be implemented in the project's stages to improve productivity.

There is always the known knows, that of human interface with such system, currently that would always be known to cause some percentage of risk with human interaction, further the system is only as good as the value of truth entered into said system, reduce the channels.of input and try to have 1 source of truth and entry, review, challenge and change accordingly

Q7. Please leave your e-mail address if you would be happy to participate in the next round of the research as well.

markjonesinoz@bigpond.com

Location Data

Location: (-31.967407226562, 115.86209106445)

Source: GeoIP Estimation