Roadmap to Mature BIM Use in Australian SMEs: A Competitive Dynamics Perspective

M. Reza Hosseini[1]; E. A. Pärn[2]; D. J Edwards[3]; Eleni Papadonikolaki[4]; Mehran Oraee[5]

Abstract

This research explores and reports upon the scale of BIM implementation maturity (from non-adoption to full-scale deployment) within Small-to-Medium Enterprises (SMEs) operating within the Australian construction industry. The research utilizes a Competitive Dynamics Perspective (CDP) as the theoretical lens and analyses data collected from 135 SMEs using Bayesian Belief Networks (BBNs) to provide a richer insight into levels of BIM implementation maturity. Findings reveal that there is no meaningful association between BIM implementation maturity within SMEs and their organizational attributes (such as size and level of experience). Additionally, lack of solid evidence to support a reasonable return on investment (ROI) was found to be the key barrier to using BIM in higher levels of maturity. In practical terms, the study focuses upon pertinent issues associated with mandated BIM in Australia from SMEs' perspective, pointing out potential consequences, and challenging the pressure for mandating. The research concludes by providing pragmatic recommendations designed to accelerate the pace that Australian SMEs move across a BIM trajectory from non-adopters to higher levels of maturity.

Keywords: Building information modeling (BIM), SMEs, adoption, implementation, antecedents, barriers, construction industry, Australia

[1] Lecturer, School of Architecture and Built Environment, Deakin University, 1 Gheringhap Street, Geelong, Victoria 3220, Australia, email: Reza.Hosseini@deakin.edu.au (Corresponding Author)
[2] Lecturer, Faculty of Computing, Engineering and the Built Environment, City Centre Campus, Millennium Point, Birmingham B4 7XG, United Kingdom, email: erika.parn@bcu.ac.uk
[3] Professor, Faculty of Computing, Engineering and the Built Environment, City Centre Campus, Millennium Point, Birmingham B4 7XG, United Kingdom, email: david.edwards@bcu.ac.uk
[4] Lecturer, The Bartlett School of Construction & Project Management, University College London, London, United Kingdom, email: e.papadonikolaki@ucl.ac.uk
[5] PhD Candidate, School of Architecture and Built Environment, Deakin University, 1 Gheringhap Street, Geelong, Victoria 3220, Australia, email: moraeena@deakin.edu.au

Introduction

Building Information Modeling (BIM) is a relatively new disruptive innovation for the construction context (Tulubas Gokuc and Arditi 2017). The term 'BIM use' captures the status of BIM execution on construction projects, covering an entire range (Chong et al. 2016). Various levels are deployed to represent the gradual use of BIM from its entry-level (basic form in adoption point) to the most complex, namely, fully integrated form (ACIF and APCC 2017; McCuen et al. 2012). And 'adoption', refers to a final stage in a decision making process that culminates in resolution to adopt and use an innovation, namely a new system, process or idea within a construction context (Tulubas Gokuc and Arditi 2017).

BIM adoption (and subsequent implementation) has been largely inconsistent across different counties (Kim et al. 2017; Ozorhon and Karahan 2017). As for the Australian context, the adoption of BIM is accelerating, with significant progress in using BIM over the last decade (Atazadeh et al. 2017). Notwithstanding these achievements, there is still a special need for increasing the value of BIM use across the construction industry (ACIF and APCC 2017). One area of particular concern: the majority of the market is using BIM in its most basic form; to date, the Australian construction industry has not adopted BIM in its fully integrated forms (Gelic et al. 2016; Niemann 2017). Besides, evidence illustrates that Australian Small-to-Medium Enterprises (SMEs) in particular are slow to adopt full-scale BIM implementation, when compared to their large-sized counterparts (Engineers Australia 2014).

Almost 75% of SME-contracting firms are among non-adopters and only around 5% have accrued experience of fully integrated forms of BIM (Dainty et al. 2017). Nevertheless, embedding widespread and mature use of BIM is essential to an industry that is heavily reliant upon engaging SMEs (Hosseini et al. 2016; Lam et al. 2017). As asserted by Shelton et al. (2016):

> *"...smaller firms will continue to dominate the construction industry landscape far into the future."*

Such realization has stimulated increasing interest amongst practitioners and academics who have sought to discover the level of BIM adoption and implementation amongst SMEs and moreover, identify the barriers and enablers to such (Lam et al. 2017). Therefore, promoting both BIM adoption and implementation in SMEs is an important mediator for BIM proliferation throughout the construction industry (Dainty et al. 2017).

Investigators have called for shifting the research focus on BIM, from total concentration on adoption and non-adopters towards investigating different BIM functions in its integrated forms (Chong et al. 2017; Gholizadeh et al. 2018). However, the academic discourse reveals that pertinent research is largely monothematic, almost entirely focused on models, frameworks and lists of barriers to address the problem of BIM adoption in SMEs (Hosseini et al. 2016; Lam et al. 2017). For example, Hosseini et al. (2016) presented a model of barriers whilst Lam et al. (2017) proposed a decision making system to support SMEs to make appropriate decisions on BIM adoption.

To date, augmenting SMEs' decision making and investigations into BIM adoption have predominated. And implementation of BIM in SMEs post adoption has received scant attention (Gholizadeh et al. 2018; Hosseini et al. 2016). It is still unknown what factors drive integrated forms of BIM use in Australian SMEs. Responding to this questions will contribute to form a shared knowledge resource. This provides a reliable basis for government, community of BIM practitioners, and service users in Australia to work together in maximizing the values of BIM in Australia, an urgent need for the Australian construction industry (ACIF and APCC 2017).

This study is driven by this fundamental need. At the objective is providing insights into the factors that affect using integrated forms of BIM among Australian SMEs. In so doing, the study explores the relationship between SMEs attributes and BIM use, and defines the main barriers to integrated forms of BIM use.

SMEs in Construction

SMEs broadly fall within three categories, namely micro, small and medium-sized enterprises, and are defined as having ≤ 4 employees, 5 and 20 and 20 – 200 employees respectively (ABS 2009).

SMEs represent around 98% of the construction sector in countries such as Australia, the US, the UK and Canada (Shelton et al. 2016); where up to 70% of this total are micro businesses (Forsythe 2014; Killip 2013; Poirier et al. 2015). Likewise, in the European Union (EU), around 99% of firms within the Architectural, Engineering, Construction and Owner-operated (AECO) sector are SMEs (Papadonikolaki et al. 2017), where 95% are micro-enterprises (Ueapme 2017). Therefore, studying BIM use within SMEs has global significance and impact reach (Dainty et al. 2017) because they are the cornerstone of a nation's economy's prosperity and dominate the construction market on a global scale (Chen and Miller 2012; Killip 2013). Compared against their larger counterparts, SMEs are typically: nimbler in terms of their structure; are more agile and can move faster to exploit new business opportunities in the market (Engineers Australia 2014; Rosenbusch et al. 2011). There is ample evidence that significant innovation can occur within SMEs (Ayirebi et al. 2017). Yet despite these, SMEs struggle to maintain their competitive edge due to the lack of sufficient resources and key assets (Lam et al. 2017; Shelton et al. 2016). Academic scholars assert that SMEs typically lag behind large-sized firms in embracing innovative technological advancements (such as BIM) and are thus unable to reap concomitant performance enhancements (Forsythe 2014; Lam et al. 2017; McGraw-Hill 2014; Poirier et al. 2015; Shelton et al. 2016).

BIM Use

Whilst BIM represents a technological innovation, the processes of applying BIM in construction organizations can be conceptualized through the lens of innovation diffusion theory (Cao et al. 2017; Gledson 2016; Poirier et al. 2015; Tulubas Gokuc and Arditi 2017). Consequently, the first engagement of companies with BIM involves making a decision on either using BIM or persevering with traditional methods (Tulubas Gokuc and Arditi 2017)– a process often based upon: market pressure (Lee et al. 2015; Zhang et al. 2018); clients' demands (Lee and Yu 2016; Lee et al. 2015; Papadonikolaki and Wamelink 2017); and bandwagon impacts, namely, pressures stemming from awareness of the sheer number of firms that have already adopted BIM (Kale and Arditi 2010). An introspective evaluation of company capabilities in providing essential resources is similarly influential (Cao et al. 2017; Jin et al. 2017; Kale and Arditi 2010; Lee et al. 2015; Newton and Chileshe 2012).

For firms opting into BIM adoption, the next steps require an incremental and sustained shift to BIM implementation; a process defined by several maturity stages (ACIF and APCC 2017; McCuen et al. 2012; Succar 2009). BIM maturity models are based on 'stages theory', representing a step-by-step evolution of a process according to well-defined milestones (Liang et al. 2016). There are various systems for defining maturity levels in BIM use (Chong et al. 2016), each with unique areas of emphasis, strengths, weaknesses and/ or specifically designed for a certain group of BIM users (Liang et al. 2016; Wu et al. 2017) – yet, curiously there is no universally accepted system (Wu et al. 2017). BIM implementation can occur in three consecutive evolutionary stages as asserted by Succar (2009): *stage 1* - object-based modelling; *stage 2* - model-based modeling; and *stage 3* – materialization of network-oriented integration. Papadonikolaki et al. (2016) classified BIM implementation process into *ad-hoc,* linear or distributed depending on the extent of digital and organizational functionalities used across the supply chain. From another perspective, the National Building Specification (NBS 2014) classified BIM implementation within firms into four different levels, namely: *level 0* - unmanaged CAD in 2D documentations with paper or electronic data exchange; *level 1*- CAD in 2D or 3D formats to present design through a collaborative tool and a common data environment (CDE); *level 2* - 3D formats through an individual BIM platform and software tools are utilized, with data attached including 4D (time) and/or 5D (cost) data; and *level 3* - a fully integrated and collaborative real-time project model facilitated by web services. These levels along with the pre-BIM status provide a straightforward benchmark for assessing the maturity of BIM engagement within construction companies (c.f. Khosrowshahi and Arayici (2012). Consequently, this 4 level system (0-3) was adopted for this research, given its wider acceptance in the field and flexible operational considerations (Liang et al. 2016). Soo too, this classification was in consistency with ACIF and APCC (2017) in defining various levels of BIM use for the Australian context.

Factors Associated with BIM Use

Various factors are associated with a firm's willingness, motivations and capacity to adopt BIM but prominent demographics include: company size, clientele, history/experience of the firms (Cao et al. 2017; Lee et al. 2015), along with their role in the construction supply chain (Ashcraft 2008; McGraw-Hill 2014; Papadonikolaki and Wamelink 2017; Tulubas Gokuc and Arditi 2017).

Role

BIM use across the construction supply chain is typically demanded by those playing the client or owner role *ad interim* (Papadonikolaki et al. 2017), given that BIM use increases their involvement in delivering projects (Cao et al. 2017; Kim et al. 2017; Zhang et al. 2018). BIM use amongst individuals within a project management team (architects, owners, contractors etc.) varies as each party is confronted with disparate challenges that are unique to that role (Ashcraft 2008; Papadonikolaki et al. 2017). Consequently, various roles across the construction supply chain show different levels of interest towards BIM (ACIF and APCC 2017; McGraw-Hill 2014).

Company Size

Eadie et al. (2013) proffered that company size is an important determinant of BIM use while Jaradat and Sexton (2016) and Hosseini et al. (2016) claimed that construction management research conducted has favored BIM adoption in large practices and megaprojects – such work has inadvertently created the impression that BIM is for large organizations. In support of this largely unsubstantiated conjecture, Dainty et al. (2017) stated that BIM uptake is:

> "*likely to be more problematic for smaller firms without the resources and capacity to invest in the technology*."

Dainty et al. (2017) implies that a cavernous *'digital divide'* has transpired between SMEs, large firms and their respective BIM adoption level - caused by insufficient resources, finance and/ or knowledge or skills inherent within the workforce (Eadie et al. 2013). Large firms are eager to adopt BIM because it is considered as strategically important to drive business growth (Acar et al. 2005; Shelton et al. 2016); (Barata and Fontainha 2017). However, Acar et al. (2005) found that the business characteristics of construction SMEs are heterogeneous and therefore size is not the only characteristic that influences BIM use.

Clientele

As BIM increasingly gains popularity, numerous construction clients are desirous to explore and profit from BIM's acclaimed benefits accrued during the production and operation of a building or infrastructure asset (Chong et al. 2016; Zhang et al. 2018). This growth has been fortified by industry reports that claim that most owners in the US (69%) and UK (80%) are positive in their overall assessment of BIM (McGraw-Hill 2014). However, UK clients feel that the UK Government's BIM mandates are:

> *"forcing them to adopt BIM, regardless of their own interest in doing so."* (McGraw-Hill 2014)

This highlights an important interdependence between clients and governmental regulation, which might be a driver for increasing BIM use across countries in the future (Ozorhon and Karahan 2017; Porwal and Hewage 2013). However, in countries where BIM is not mandated for public projects (such as Australia), other actors (such as leading and innovative contractors and consultants) might be equally dominant and influential in driving the agenda (Engineers Australia 2014; Hosseini et al. 2016; Papadonikolaki et al. 2017).

History/ Experience

Another prominent factor underpinning BIM adoption is a firm's clientele (Rodgers et al. 2015; Zhang et al. 2018), related to its history and experience (Eadie et al. 2013). A firm's history and project portfolio (i.e. what balance of public vis-a-vis private projects are undertaken), can determine their motivation and urgency to use BIM in projects (Eadie et al. 2013; Lee and Yu 2016). According to Arayici et al. (2011), a firm's past experience of BIM and '*forward thinking top management'* who are be supportive of this process are decisive ingredients for the successful adoption and implement of BIM. A firm's history and experience also has great affinity to any long-term relations or repetitive projects. For example, long-term partnerships in the Netherlands (where alliancing is popular) tend to regulate each other by jointly deciding to use BIM in their projects

(Papadonikolaki and Wamelink 2017). This is related to meso-level mimetic mechanisms that constitute a contributing factor to macro-BIM adoption (Succar and Kassem 2015). When SMEs partner with larger and established firms they gain access to a greater market share, clientele and resources (Manley 2008). Barata and Fontainha (2017) support this assertion and state that '*internationalization contributes to innovation*' and that firms experienced in the international market tend to be more innovative than firms at a national, regional or local level. Put simply, level of awareness of clients and key stakeholders of the benefits associated with BIM use, correlated with their experience and connections with the market, is an influential factor for companies to use BIM (Newton and Chileshe 2012; Ozorhon and Karahan 2017; Rodgers et al. 2015).

Barriers to Mature Use of BIM in SMEs

Various factors can hinder BIM use (Eadie et al. 2013; Lee and Yu 2016) albeit, there is a dearth of research from an SME's perspective (Dainty et al. 2017; Hosseini et al. 2016). Barriers identified can be categorized into three thematic categories, namely: i) demand for, and inter-organizational capabilities to supply BIM work; ii) intra-organizational resources; and iii) firms' perceived benefits of BIM implementation (Lee and Yu 2016). Table 1 tabulates the barriers to mature levels of BIM use in SMEs, with input from the items identified by Hosseini et al. (2016).

<INSERT TABLE 1 HERE>

Demand and Supply

Several scholars have reported upon a lack of client demand for investing and using BIM (Aibinu and Venkatesh 2014; Goucher and Thurairajah 2012; Rodgers et al. 2015). In addition, Won et al. (2013), suggests that not all projects are appropriate for BIM use for example, small projects can be too simplistic realize the maximum benefits of BIM. Firms may struggle to align BIM implementation with the inter-organizational capabilities supplied by their counterparts and partners (Papadonikolaki et al. 2016; Papadonikolaki and Wamelink 2017).

Intra-organizational Resources

At an intra-organizational level, limited resources within SMEs influence their ability to use BIM in projects (Eadie et al. 2013). Financial barriers of BIM are pervasive and include software and licenses procurement and hardware upgrades that proportionally, represent a far greater burden for SMEs (Aibinu and Venkatesh 2014; Ganah and John 2014; McGraw-Hill 2012; Yan and Demian 2008). In addition to the cost of investing in BIM infrastructure, the time and cost required to train staff are the largest barriers to BIM adoption and are particularly influential on SMEs (Aibinu and Venkatesh 2014; Becerik-Gerber B. 2011; Eadie et al. 2013; Yan and Demian 2008). Even when knowledgeable people are trained, found and employed, their existing skills-set must be continually upgraded via continuous professional development to keep them abreast of the latest advancements. Managing change and ensuring trust among the team represent further considerations amongst firms striving to transform their business to embrace BIM adoption (Aibinu and Venkatesh 2014; Cao et al. 2014; Papadonikolaki et al. 2017; Papadonikolaki et al. 2016; Won et al. 2013). Indeed, Azhar (2011) purports that the barriers to BIM use are either technical or managerial, whilst Won et al. (2013) and Zhang et al. (2018) proffer that managing the non-technical organizational issues is more urgent than technical barriers.

Perceived Benefits

Firms may display a lack of motivation to use BIM when the technology: *"is perceived to be flawed in terms of user-friendliness, usefulness, attractiveness and affordability."* (Dainty et al. 2017) Prominent and omnipresent issues such as the lack of interoperability between different platforms and proprietary files is a notable barrier to utilizing BIM to its full potential (Aibinu and Venkatesh 2014; Demian and Walters 2014). Similarly, Arayici et al. (2011) reported upon the struggles associated with having a common language for data exchange in a BIM environment. Yan and Demian (2008) also discovered that a significant percentage of organizations believed that BIM is unsuitable for their current projects and that existing technologies were sufficient for delivering their services. Thus, the above effectuate lack of senior management buy-in towards BIM adoption (McGraw-Hill 2012).

Theoretical Lens of Competitive Dynamics Perspective

While BIM is a disruptive technological innovation (Cao et al. 2014; Poirier et al. 2015), the term 'BIM use' refers to both BIM adoption and implementation in understanding BIM execution features (Chong et al. 2016). Hence, studying the behaviors of SMEs towards BIM use must consider all influential external and internal motivators acting upon a firm (Tulubas Gokuc and Arditi 2017). Evidence illustrates that the perceptions of key decision makers in SMEs (regarding BIM's potential to enhance performance and strengthen market position) are pivotal to BIM adoption (Dainty et al. 2017; Hosseini et al. 2016; Newton and Chileshe 2012). Specifically, return on investment and a robust financial assessment of the essential resources required are the most influential factors shaping these perceptions and consequently, the behavior of SMEs towards BIM (Kim et al. 2017; McGraw-Hill 2014; Poirier et al. 2015).

With the aforementioned in mind, this research draws upon a Competitive Dynamics Perspective (CDP) (Ketchen et al. 2004), as the theoretical lens to explain and interpret the observed behaviors of SMEs towards BIM use. The foundation of CDP is grounded in providing insights into the interactions of organizations that embrace new products, and explaining managers' behaviors in attempting to maximize firms' profit and performance (Ketchen et al. 2004). CDP is an effective explanatory tool for linking strategic decisions, actions and processes, resource-oriented considerations, and market perspectives on innovations and new products (Chen and Miller 2012). This theoretical lens has the inherent ability to explain the behavior of organizations towards the market and profit effects of innovative actions (Smith et al. 2001). These features make CDP an effective approach to explaining the behavior of SMEs towards BIM use.

Research Approach

Behavior of construction practitioners (including those working for SMEs) towards any innovation is shaped by their assumptions and perceptions of it (Kale and Arditi 2010; Shelton et al. 2016); investigating perceptions as subjective phenomena, necessitates building awareness of the behavior of individuals. To elicit knowledge from practitioners in SMEs (the target population), quantitative data collection was deemed a suitable method, given its capability to generalize findings (Mackenzie and Knipe 2006). A questionnaire survey is a ubiquitous quantitative data collection instrument, designed to: elicit knowledge; give meaning to the aggregated behavior of a group of individuals; and discern existing patterns of association (Robson 2002). With the aforementioned in mind, a survey questionnaire among Australian SMEs was selected and further description is herein further elucidated upon.

Rationale and data collection

Availability of the questionnaire deployed to measure the adoption of BIM by South Australian SMEs (c.f. Hosseini et al. (2016) was construed a unique opportunity, offering the research team a sound basis to develop a survey instrument. That was because, developing a new instrument is not recommended, particularly if a reasonable instrument is already available (Chileshe and Kikwasi 2014; Punch 2005). According to Punch (2005): "… we would need good reason for passing over an already existing instrument." The aforementioned questionnaire was selected given that: (1) previously used instruments are extensively tested at the time of use and can provide a robust, valid and reliable data collection instrument (Chileshe and Kikwasi 2014); (2) the questionnaire was recent, exclusively developed for Australian SMEs, where the objectives were relatively similar to the present study. As such, the questions were deemed reflective of recent developments in BIM, anchored to the realities of SMEs and the Australian context alike. Such context specific similarity is another reason for using surveys from past empirical studies. So too, such an approach provides opportunities for cross-comparative analysis (Chileshe and Kikwasi 2014).

The questionnaire was revised to incorporate the concept and levels of BIM implementation. Within the questionnaire's preliminary section, key terms such as BIM and levels of BIM implementation were explained and defined using professional expressions rather than academic terms. A description of the research project's aims was also given and some rudimentary questions were presented to identify the respondents' demographic profile. The questionnaire's second section included statements describing the barriers, which make construction practitioners in SMEs shy away from moving to higher levels of BIM implementation. Respondents were asked to rate their level of agreement with regard to the influence of the described barriers via a five-point Likert-item rating where (1 = *strongly disagree,* 2 = *disagree,* 3 = *neutral*, 4 = *agree, and 5 = strongly agree*). Likert scale surveys with five categories are very common in construction management research (Holt 2013), and as such, utilized in the present study.

Sampling process

The study by Hosseini et al. (2016) elaborated on the details of SMEs in the Australia construction industry and detailed the determination of them as the target population. In view of the common population and alike research objectives, the sampling strategy by Hosseini et al. (2016) was emulated in the present study. This is an acceptable approach for reporting and justifying the research design (Ye et al. 2013). For the sake of brevity, details about the target population and sampling strategy are not presented here. A total of 1,365 (712 architects/ design firms and 653 contractors) questionnaires were distributed by post to company headquarters and follow-on emails posted to directors of these companies. A total of 149 completed questionnaires were returned, demonstrating a response rate of 11% - such was previously deemed acceptable within contemporary construction management research (Bing et al. 2005). The data collection commenced October 2015 and was finalized in February 2016. Of these questionnaires, 135 fell within the category of SMEs and the rest 14 completed questionnaires were from large-sized companies and hence, were omitted from further analysis. Therefore, these residual 135 questionnaires formed the basis for data analyses. Of these 135 questionnaires, 57 (~ 42%) were found to be implementing BIM in various levels on their projects, and thus their completed questionnaires were deemed usable for analysis of BIM implementation.

Table 2 reports upon the demographic profile of Australian SMEs represented in the dataset of the study. Regards size of firm, 126 out of 135 (~ 93%) were micro and small businesses while medium sized companies constituted the remaining ~ 7% of sample SMEs. 128 of participants (~ 95%) were working with owners/ individuals or private organizations, exposing their predominant reliance upon the private sector and *de facto* exclusion from government contracts. Close to 39% of respondents represented contractor/ builder companies, whereas design companies made up ~ 61% of the sample.

<INSERT TABLE 2 HERE>

Sample demographics provided evidence of the adequacy of respondent knowledge completing the survey. That is, 124 out of 135, namely ~ 92% of participants were from companies with > 11 years of experience within the construction industry, denoting their involvement and awareness of developments occurring in the industry and awareness of a shift from traditional methods of project management towards BIM. Further, 119 (~ 88%) of respondents were directors and project managers of companies (refer to Table 2) and essentially key decision makers within their organizations. Thus, survey respondents were immersed in decision making processes and related procedures, thus denoting their first-hand involvement and awareness of company policies and strategies with regard to BIM.

From Data to Analysis

As discussed, items (questions), were adapted from a previously used questionnaire. Testing the internal reliability of a questionnaire developed in this way was deemed necessary. *Cronbach's alpha coefficient* is the most frequently used reliability statistic for scales comprised of multiple items (Punch 2005). The items in the present study were not used to measure one particular construct. In fact, they were unrestrictive measures to reflect the same latent dimension with different precision, termed by Raykov (1997) as *congeneric measures*. The most accurate reliability test for congeneric measures is the Composite Reliability (CR) index (Hair et al. 2014; Raykov 1997). Following the instructions provided by Hair et al. (2014), the CR value was calculated based on conducting factor analysis: rotated component matrix (Varimax technique), and inclusion of 4 extracted factors. The CR value turned out to be 0.887, where values of CR between 0.70 and 0.90 are regarded as satisfactory to establish the reliability of items of a questionnaire survey (Hair et al. 2014).

Bayesian Belief Networks (BBNs) are efficient tools to facilitate accurate reasoning when limited data are available from a real-life complex environment (Ben et al. 2007; Conrady and Jouffe 2015). Survey data reflect the perceptions and knowledge of human beings but are fraught with high levels of uncertainty - BBNs are capable of dealing with such uncertainty effectively and efficiently (Chen and Pollino 2012). These capabilities of BBNs were applicable to the research problem, particularly for analyzing the study's relatively small sample size (57 completed questionnaires for analyzing various levels of implementation) for which statistical methods were not deemed to be appropriate. With these facts in mind, BBNs were selected; a schematic of analytical methods and associated techniques are reproduced in Figure 1 for brevity.

<INSERT FIGURE 1 HERE>

Unsupervised learning through the Maximum Weight Spanning Tree (MWST) algorithm was utilized due to its proven efficiency and simplicity to identify associations among variables in a dataset. Given, the nature of variables, following a non-normal distribution, Minimum Description Length (MDL) scoring was implemented. BBNs also enable researchers to concurrently integrate theories with knowledge extracted from the dataset for analytic modelling (Conrady and Jouffe 2015). Therefore, models submitted to supervised learning were deemed capable of integrating the associations identified through unsupervised learning with previous findings from the literature (see Figure 1). Supervised learning focuses on exploring a target variable in the model, particularly to identify the most relevant variables in characterization of the target node by comparing the strength of associations among a target and its predictors. The most efficient variable selection technique for BBNs is Markov Blanket (Conrady and Jouffe 2015), which was the primary technique used to identify the most relevant variables affecting target variables. BBNs are natively probabilistic, omni-directional and capable of trying out various scenarios to capture the uncertainty of human perceptions. The entire joint probability distribution of variables in the system were included to handle different scenarios regarding the problem, using Conditional Probability Tables (CPTs). These tables act as inference engines that relate states of various variables, and enable researchers to simulate various scenarios for all possible combinations of variable values. Using CPTs however, necessitated developing a model to define the associations between the variables included. The commercially available BayesiaLab software was used to conduct the analysis (c.f. Conrady and Jouffe (2015), as this package provides a complete set of Bayesian network tools including unsupervised and supervised learning.

Findings of the Study

Once a BBN model is fully specified, CPTs can compute the underlying probabilities and the strength of associations between variables in view of the assumptions or evidence about the state of the parents of variables (Chen and Pollino 2012). BBNs deal with two or more variables that are related to each other in a model. These variables are typically discrete variables, namely, each one can only take a number of possible values. The rule at the very heart of the BBN analysis suggests that if $\boldsymbol{x_i}$ is some value for the variable $\boldsymbol{X_i}$ ($\boldsymbol{x_i}$ is one possible value of the variable $\boldsymbol{X_i}$) and $\boldsymbol{pa_i}$ represents some set of values for the parents of $\boldsymbol{X_i}$ ($\boldsymbol{pa_i}$ is a possible value for the variables that are defined as the parents of $\boldsymbol{X_i}$ in the model) then $\boldsymbol{P(x_i|pa_i)}$ indicates this conditional probability distribution. Generally, the global semantics of BBNs specifies that the full joint probability distribution (JPD) is given by the chain rule, illustrated in Equation 1.

$$P(x_i, \dots \dots \dots., x_n) = \prod_i P(x_i|pa_i) \qquad \text{Equation 1}$$

To build the engagement model (refer to Figure 2), attributes of SMEs along with their BIM implementation levels were included as variables. Associations were defined based on the review of literature to incorporate the impacts of *size*, e*xperience*, *role*, and c*lient* (four predictors) on i*mplementation level* of SMEs (the target variable). To integrate these associations with the knowledge provided by the dataset, unsupervised learning was conducted through a MWST algorithm and MDL scoring method, in order to capture any dependencies between the variables. This resulted in identifying a link between the s*ize* and the c*lient*, as illustrated in Figure 2.

<INSERT FIGURE 2 HERE>

The strength of associations between variables in a model can be accurately assessed using the concept of *mutual information*, which is reflected in the value of *Arc's Mutual Information* between variables. Arc's Mutual Information value shows which variable as the predictor provides the maximum information, thus has the greatest importance to predict the state of the target node in the model. Specifically, the value indicates the state of each variable in the model and what percentage uncertainty will be reduced for the variable on the opposing side of the link (Conrady and Jouffe 2015). Arc's Mutual Information value is calculated using Equation 2 for any pair of variables such as (x, y) (c.f. Conrady and Jouffe (2015) for further details).

$$I\ (x, y) = \sum_{x \in X} \sum_{y \in Y} p(x, y) \log_2 \frac{p(x,y)}{p(x)p(y)} \qquad \text{Equation 2}$$

Having performed the supervised learning analysis of nodes through Markov Blanket, the model in Figure 2 demonstrates the values (highlighted in blue) of Arc's Mutual Information between the variables on both sides of the links. Three values related to Mutual Information are represented graphically in the thickness of the arcs in Figure 2. The top number shows the actual value of the Mutual Information of the link, as a symmetric measure. The value in the middle is the Relative Mutual Information with regard to the child node. And the value at the bottom shows the Relative Mutual Information with regard to the parent node (Conrady and Jouffe 2015).

With the above in mind, referring to Figure 2, knowing the size of a company, means that uncertainty regarding its BIM implementation level can be reduced by 3.56% on average. Similarly, awareness of the amount of experience of a SME in the market and the type of client can reduce the level of uncertainty on BIM implementation level by 2.95% and 2.98% (on average) respectively. Given, the low values provided by the model, a relationship analysis was conducted to assess whether associations are significant (refer to Table 3).

<INSERT TABLE 3 HERE>

BayesiaLab assesses the dependency using two different approaches, namely: i) *G-test* of independence; and ii) *Kullback-Leibler Divergence*. The G-test tests the dependency on categorical or nominal variables, to assess the dependency of proportions, whereas *Kullback-Leibler*

Divergence is an information-based test of disparity among probability distributions of variables (c.f. Joyce (2011) for a comprehensive treatment of this subject). As illustrated in Table 3, for both the tests, *p-values* were well above 0.05, indicating no significant association between s*ize*, *role*, e*xperience*, and c*lient* with BIM *implementation level*. That is, none of these characteristics define the level of BIM implementation for SMEs. SMEs in any size, with any level of experience, in all typical roles, and clientele have similar behavior towards BIM use.

Barriers to BIM use in higher maturity

To analyze the associations between different levels of BIM implementation and barriers to each one, the 4-levelled categorization of BIM maturity was used. The barriers identified from the literature (see Table 1) were defined as the variables. An unsupervised learning through a MWST algorithm and MDL scoring method was performed to reveal any hidden association among the included variables. This resulted in identifying associations between 'Barr 04' (*perceived low benefits of BIM*) with 'Barr 01' (*lack of demand for high-level of BIM implementation*) and 'Barr 08' (*perception of limited functionality of higher levels of BIM for SMEs*). The level of BIM implementation was defined as the target variable and barriers were considered as predictors of this target variable. These considerations resulted in the creation of the model illustrated in Figure 3.

<INSERT FIGURE 3 HERE>

The dependency among the variables included in the model was assessed through two different tests of dependency for categorical and nominal variables. As such, the *G-test* of independence, and *Kullback-Leibler Divergence* were performed (refer to Table 4) and illustrated that none of the barriers were significantly associated with the level of implementation. There was no meaningful association between the barriers and the levels of BIM implementation. Consequently, the included barriers can be deemed similarly influential across various levels of BIM use, regardless of the current and target BIM use levels. That is, companies that intend to move from Level 0 to Level 1, from Level 1 to Level 2, and from Level 2 to Level 3 face similar challenges in their transitions.

<INSERT TABLE 4 HERE>

Nevertheless, the associations between Barr 04 and Barr 01, and Barr 04 with Barr 08 were found to be significant, with both techniques showing *p-values* below 0.05 (see Table 4). To identify the most influential barriers affecting the level of implementation, a CPT was utilized, linking the level of implementation as the target, and barriers as predictors of this target variable.

The barriers were sorted based on the mutual information values and calculated based on Equation 2 to create Figure 4. That is, the level of influence of barriers was defined according to the amount of information that each one provides, to predict the level of implementation of BIM in SMEs (refer to Figure 4). It is noteworthy of mentioning that Figure 4 relates states of various variables (barriers and implementation values) in the dataset, where no simulations scenario is applied. Therefore, each vertical axis in each cell shows the percentage of responses to various levels of the Likert scale (1- 5 are referred to in three categories: <=2, <=3, >3), for the current percentages of BIM implementation, as reflected in the dataset.

<INSERT FIGURE 4 HERE>

Based upon Figure 4 and Table 4, the most influential barriers were found to be Barr 08, Barr 04, and Barr 01, which can be attributed to the limited perceived functional value of migrating to higher levels of BIM, along with the adequacy of current levels. The second group of sorted barriers all referred to the required resources for shifting to higher levels of BIM. That is, Barr 05 (significant transition costs for BIM implementation), Barr 02 (*lack of knowledge on managing the process of BIM adoption*) and Barr 03 (*shortage of skills and expertise for high-level of BIM implementation*). The barriers that displayed the least amount of influence were found to be Barr 09 (*immaturity of BIM technology for high-level of BIM implementation*), Barr 06 (*lack of clients' demand of BIM use*) and Barr 07 (*perceived lack of suitability of BIM for all building project types*). These for the most part were reflective of particular features of the projects delivered by SMEs, such as the lack of functionality of BIM for the project delivered by the company and lack of interest from clients in such projects.

Discussion of the Findings

The study's findings revealed certain original views and new insights with regard to BIM use in Australian SMEs. Overall, the study's theoretical contribution provided a pragmatic view of BIM use by studying both adoption and implementation from the perspective of construction SMEs (and thus interacting with both intra- and inter-organizational levels), as underlined by the CDP perspective. The study adds to an existing knowledge base of SMEs' BIM use by offering empirical data collated through questionnaires, outlined from scientific research and analyzed in a robust quantitiative manner. Specifically, the study demonstrated no meaningful association between the attributes of SMEs and their level of BIM implementation. Previous studies such as McGraw-Hill (2014) highlighted the discrepancies between SMEs and large-sized Australian companies in using BIM, using descriptive statistics. Dainty et al. (2017) maintained that SMEs' attributes such as size are determinants of BIM engagement. The findings of this empirical research however, do not uphold these assumptions. These challenging new findings could be explained in view of the trade-off between structural and organizational flexibility and agility in smaller and newly-established SMEs, and availability of assets and resources in larger and mature ones (Amit and Schoemaker 1993). Another explanation could be the impact of context in shaping the nature of associations among attributes of companies and their behaviors towards an innovation (Rosenbusch et al. 2011). SMEs idiosyncrasies in synergy with BIM specific requirements might act as moderators to neutralize the impacts of firms' demographics.

Study findings also reveal that the key barriers preventing SMEs from implementing BIM in higher and more sophisticated maturity levels, almost entirely stemmed from the lack of solid evidence of concomitant financial benefits. The same barrier prevented SMEs from adopting BIM, as previously argued by Hosseini et al. (2016). This insight underlines the crucial role of providing a better understanding of measures for transforming BIM capabilities into tangible marketable outputs in SMEs for projects typically delivered. The limitations of SMEs in terms of available resources and knowledge were also influential barriers. Reaping the benefits of BIM in higher levels of implementation relies on establishing collaborative relationships with external entities involved in projects (Oraee et al. 2017). From the perspective of CDP, using innovative methodologies with a focus on external collaboration is fraught with risks for SMEs - that is, complicated, collaboration-oriented innovative methodologies become substantially challenging for SMEs and incur great costs (Rosenbusch et al. 2011). As smaller market participants, SMEs must follow the instructions and interests of larger organizations, and receive unfavorable terms in such collaborative relationships (Porter 2004). There is thus, additional scope to support continuous engagement of SMEs with BIM use in order to avert the impressions of a 'digital divide' that currently dominates BIM rhetoric and support a more collaborative and less competitive view of BIM in construction.

Practical Implications

Drawing upon the findings, several practical implications are suggested to promote higher levels of BIM implementation among SMEs. First, according to CDP principles, directing SMEs towards higher levels of BIM implementation is achievable by providing insights into how such a migration could be translated into profit and higher performance (Ketchen et al. 2004). This point was argued by Hosseini et al. (2016), as a remedial solution to increase the BIM adoption rate among SMEs. To mitigate the issues involved with risky, competitive and unfavorable collaborative relationships with larger organizations who exhibit a natural propensity to implement BIM at higher levels, SMEs are advised to consider developing internally-designed BIM solutions and engage in external collaborations in a dynamic manner. Initially, focusing on internal BIM development, as better insights and market recognition is gained, the focus of SMEs can progressively shift towards actively engaging with external collaborators to leverage their experiences and capabilities in BIM (Rosenbusch et al. 2011). Essentially, SMEs could manage BIM knowledge and increase their BIM learning through partnering and alliances (Papadonikolaki and Wamelink 2017). Another solution might be engaging in collaborations with other SMEs (as external partners) at initial stages where competitive dynamics are favorable and the liability of smallness is less detrimental (Rosenbusch et al. 2011).

The research findings also warrant further scrutiny of plans to pursue mandating BIM in Australia. As discussed, power relations within companies engaged in a mandated BIM collaboration network along with the inherent problems facing SMEs (such as lack of resources), might render an enforced BIM implementation strategy deeply troubling for SMEs. These perceived draconian conditions widen the knowledge and technical capabilities gap, and engender business inequality between SMEs with large-sized companies. These inequalities among construction firms tend to become more extreme in top-down BIM diffusion mechanisms (Succar and Kassem 2015), in contexts where BIM is mandated. Such a situation is counter-intuitive given the construction industry's reliance upon SMEs who often sub-contract for larger contractors and so other more encouraging and engaging strategies should be sought.

Conclusions

The study contributed to the body of knowledge on BIM-related studies devoted to BIM use amongst SMEs in several ways. First, the study is among the few that transcend the dominant approach of focusing on adoption of BIM and investigating adoption/ non-adoption behaviors. That is, the present study moves to the area of implementation and mature levels of BIM use. Second, several original insights into the problem were revealed and as such, will engender wider debate as well as encourage further investigation into the impacts of SMEs' attributes on their behaviors towards BIM use. Moreover, the findings validate the assumption that considerations are at the forefront of SME decision making regards the level of BIM implementation. A new insight proposed is the detrimental consequences of dependence on external collaboration in engaging with BIM. This also triggers further debate on the assessment of long-term consequences of BIM mandating in widening the gap between SMEs and large-sized companies in the market, an area hitherto overlooked within extant literature.

Despite these various contributions, the research has several limitations. The findings are reflective of perceptions from the context of Australian SMEs and predominantly micro-sized companies. As a result, direct translation of the findings into guidelines in other countries and for companies with glaringly different attributes should be treated with caution. This limitation however, points towards several fertile grounds for further investigation into the topic, including: assessing the validity of the findings in other contexts and countries; use of larger sample sizes; and incorporation of other interested stakeholders such as clients - where this study was limited to contractors and design companies. The focus of such future work should seek to provide additional insight into the mechanics of collaboration between SMEs, designers, clients and large-sized companies in engaging with BIM.

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Table 1. Barriers to mature levels of BIM implementation

Barrier ID	Description	Type	Source(s)
Barr 01	Lack of demand for high-level of BIM implementation	Demand and Supply	(Aibinu and Venkatesh 2014; Gholizadeh et al. 2018; Goucher and Thurairajah 2012; Lam et al. 2017; Niemann 2017; Won et al. 2013)
Barr 02	Lack of knowledge on managing the process of BIM adoption	Resources	(ACIF and APCC 2017; Aibinu and Venkatesh 2014; Becerik-Gerber B. 2011; Gholizadeh et al. 2018; Goucher and Thurairajah 2012; Newton and Chileshe 2012; Ozorhon and Karahan 2017; Rodgers et al. 2015; Won et al. 2013; Zhang et al. 2018)
Barr 03	Shortage of skills and expertise for high-level of BIM implementation	Demand and Supply	(ACIF and APCC 2017; Gelic et al. 2016; Papadonikolaki et al. 2016; Papadonikolaki and Wamelink 2017; Rodgers et al. 2015; Yan and Demian 2008; Zhang et al. 2018)
Barr 04	Perceived low benefits of BIM	Motivation	(ACIF and APCC 2017; Dainty et al. 2017; Gelic et al. 2016; McGraw-Hill 2012)
Barr 05	Significant transition costs for BIM implementation	Resources	(Aibinu and Venkatesh 2014; Cao et al. 2017; Eadie et al. 2013; Engineers Australia 2014; Ganah and John 2014; Lam et al. 2017; McGraw-Hill 2012; Yan and Demian 2008)
Barr 06	Lack of clients' demand of BIM use	Demand and Supply	(Aibinu and Venkatesh 2014; Goucher and Thurairajah 2012; McGraw-Hill 2014; Newton and Chileshe 2012)
Barr 07	Perceived lack of suitability of BIM for all building project types	Demand and Supply	(Engineers Australia 2014; Lam et al. 2017; Won et al. 2013; Yan and Demian 2008)
Barr 08	Perception of limited functionality of higher levels of BIM for SMEs	Motivation	(Engineers Australia 2014; Hosseini et al. 2016; Lam et al. 2017; McGraw-Hill 2012; McGraw-Hill 2014; Rodgers et al. 2015)
Barr 09	Immaturity of BIM technology for high-levels of BIM implementation	Motivation	(Aibinu and Venkatesh 2014; Arayici et al. 2011; Atazadeh et al. 2017; Demian and Walters 2014)

Table 2. Profile of participants

			Client / Experience								
			Government		Individual / Owner			Private organizations			Grand Total
Role	Position	Size	11-20 years	More than 20 years	11-20 years	More than 20 years	Up to 10 years	11-20 years	More than 20 years	Up to 10 years	
Contractor / Builder	Designer	5-19 employees				1					1
		20-199 employees				1			1		2
	Director	0-4 employees		3	4	12					19
		5-19 employees			6	8	1	2	1		18
		20-199 employees		1							1
	Project Manager	0-4 employees			2	2		1			5
		5-19 employees	1			1	2	1	1		6
Designer	Designer	0-4 employees			3	5					8
		5-19 employees				1			1	1	3
		20-199 employees						1			1
	Director	0-4 employees			8	31	5	2	4	1	51
		5-19 employees		2		4		2	5	1	14
		20-199 employees				1			3		4
	Engineer	20-199 employees						1			1
	Project Manager	5-19 employees			1						1
Grand Total			1	6	24	67	8	10	16	3	135

Table 3. Test of dependency between variables

Parent	Child	Kullback-Leibler Divergence	Degrees of Freedom	*p-value*	G-test	Degrees of Freedom	*p-value*
Experience	Implementation_Level	0.271	144	1.000	10.451	8	0.234
Size	Implementation_Level	0.268	144	1.000	13.737	8	0.0888
Client	Implementation_Level	0.209	144	1.000	10.534	8	0.229
Role	Implementation_Level	0.204	108	1.000	10.670	4	0.303
Size	Client	0.129	4	0.007	24.257	4	0.007

Table 4. Test of dependency between the level of BIM implementation and barriers

Parent	Child	Kullback-Leibler Divergence	Degrees of Freedom	*p-value*	G-test	Degrees of Freedom	*p-value*
Barr 04	Barr 08	0.380	4	0.002	26.396	4	0.0026
Barr 04	Barr 01	0.360	4	0.005	24.998	4	0.0050
Barr 07	Implementation Level	0.013	26244	1.000	1.740	4	0.783
Barr 06	Implementation Level	0.013	26244	1.000	1.479	4	0.830
Barr 02	Implementation Level	0.013	26244	1.000	2.502	4	0.644
Barr 03	Implementation Level	0.012	26244	1.000	2.847	4	0.583
Barr 09	Implementation Level	0.012	26244	1.000	1.680	4	0.794
Barr 05	Implementation Level	0.010	26244	1.000	4.165	4	0.384
Barr 08	Implementation Level	0.010	26244	1.000	6.992	4	0.136
Barr 01	Implementation Level	0.009	26244	1.000	2.961	4	0.564
Barr 04	Implementation Level	0.006	26244	1.000	1.734	4	0.784