Current perspectives and future directions of BIM assessment methods

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Abstract

The past century has witnessed significant developments in the field of Performance Measurement Systems (PMSs) in a wide range of disciplines, such as business management, engineering and computer science. Since 2007, PMSs have emerged in the Building Information Modelling (BIM) domain, with at least sixteen BIM Assessment Methods (BIM-AMs) developed to date, in both academia and industry. The need for BIM-AMs has been widely recognised, since they help businesses to track their progress of BIM Implementation and compare their capabilities against other companies. But despite these recent developments, BIM-AMs still face some fundamental challenges, in particular the way most assessments still rely on qualitative and subjective judgements, raising questions over accuracy, practicality and validation.

This research presents a new approach to BIM-AMs and combines theory with practice. On the theoretical side, the thesis starts with a comparative overview of current Assessment Methods (AMs) to explore their various characteristic including what they evaluate (projects, organisations, teams or individuals), their range of measures and the way in which they communicate results. On the practical side, three AMs are applied to real case study projects in association with multiple Architecture, Engineering and Construction (AEC) companies. This combination of theory and practice expands and challenges what is currently known about BIM-AMs. It offers a solid foundation to build more in-depth research on BIM measurement.

In order to optimise the current AMs, an automated plug-in is developed to measure the Level of Detail of model elements. The automation of BIM assessment is shown to have the potential to deliver less qualitative, more objective and practical approaches of assessment. It has the potential to turn subjective and qualitative measures into quantifiable and objective data and provides fast and user-friendly assessment for the AEC businesses.

The positive impact of BIM-AMs has been recognised by academics, professionals and policy-makers. Existing AMs have contributed enormously to the field of BIM assessment, but they will only lead to sharper and more efficient businesses if coupled with automation in evaluation and innovation in choosing appropriate measures.

Acknowledgements

Thanks to my doctoral supervisors Dr. Alex Copping and Dr. Paul Shepherd for their invaluable advice on the development of this research. Alex and Paul have sharpened my understanding of this research, offered a critical and intellectual engagement with my work and encouraged me to take my research skills and knowledge out of the university; building bridges between academia and practice and between academia and the local community.

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The chapters in this thesis benefited significantly from the discussions and the views of the experts and professionals who showed great belief in this research. I am particularly grateful for the collaboration with Mr. Andrew Duncan and Mr. Paul Hill of Arup, London.

I am thankful for the tremendous encouragement of many colleagues and friends. They have been my second family. I am deeply appreciative to my parents in Homs, Syria, and my sisters, for their unlimited love. They have been my endless source of strength, hope and inspiration.

This thesis is dedicated to my country, Syria and its suffering people. My thoughts have been with them.

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List of Acronyms

AEC	Architecture, Engineering and Construction
AIA	American Institute of Architects
BEP	BIM Execution Plan
BIM	Building Information Modelling/Model/Management
BIM-AM(s)	BIM Assessment Methods
BIMCAT	BIM Competency Assessment Tool
BIM-MM	BIM Maturity Measure
BRE	Building Research Establishment
CAD	Computer Aided Design
CIBSE	Chartered Institution of Building Services and Engineers
CIFE	Centre for Integrated Facility Engineering
CMM	Capability Maturity Model
CPI	Construction Project Information
CSP	Case Study Project
ICMM	Interactive Capability Maturity Model
iBIM	Integrated BIM
IFC	Industry Foundation Classes
LOD	Level of Detail/Development
NBIMS	National BIM Standard
NIBS	National Institute of Building Sciences
PMS(s)	Performance Measurement System(s)
RIBA	Royal Institute of British Architects
SEI	Software Engineering Institute
UKAS	UK Accreditation System
VDC	Virtual Design and Construction

1 Introduction to the research

This chapter provides a background on Building Information Modelling (BIM), its emergence and definitions. The problem statement of the research, the research justification and its aim and objectives are introduced before a comprehensive review of performance measurement systems is discussed in Chapter 2.

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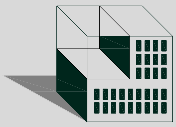
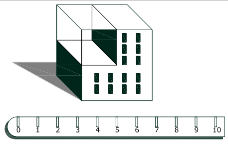
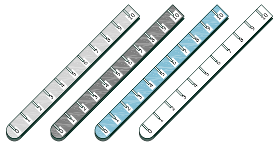
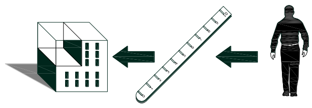
		
Main questions included: What is BIM? What is the need for BIM-AMs?	Includes: - Brief history of the broad PMSs, their definitions - PMSs roles and barriers - Sample of PMSs	- Explains the wide range of BIM-AMs, their evolution, opportunities and challenges - Investigates how BIM-AMs have been informed by the broader PMSs
4: Research methodology	**5: Perspectives on BIM-AMs**	**6: Pilot Testing**
		
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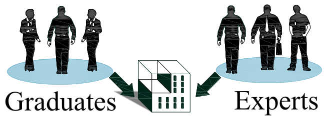
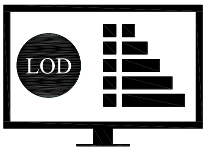
7: Comprehensive testing	**8: Automated BIM-AM**	**9: Conclusions**
		
In association with Arup, applying three AMs to the same project and completed by six participants who have different BIM experience i.e. experts and graduates	Includes: - The need for automated AMs - The implementations of BIM-AM in practice	Current perspectives and future directions of BIM-AMs

1.1 Introduction

For as long as they have existed, buildings have been imagined and communicated through a wide range of techniques. From pen and ink drawings of Da Vinci and Michelangelo, collage by Renzo Piano and Richard Rogers in the 1970s, and paintings of Zaha Hadid in the 1980s, traditional hand-drawings have been the most widely applied technique in the history of architecture.

Since the 1960s, the Architecture, Engineering and Construction (AEC) industry has applied Computer Aided Design (CAD) system, with wider adoption in the 1980s (Volk et al., 2014). The implementation of CAD has assisted the AEC sector to represent the geometric information of projects (Kam et al., 2013b). But the sector, however, has relied heavily on the traditional exchange of 2D drawings instead of innovating in 3D models (Singh et al., 2011). CAD system has been criticised for its poor documentation, labor-intensive, error-prone processes (Eastman et al., 2011), lack of effective design management and communication, and duplications (Arayici et al., 2011). Independent 2D views of a building, i.e. plans, elevations and sections, are updated and checked individually, rather than being intelligently connected (Azhar et al., 2008). CAD limitations have been further discussed by Shepherd and Richens (2012) who note:

> CAD was simply seen as an electronic version of paper, used for its ease of editing, storage and printing, rather than as a tool for analysis in itself. Whilst engineers in other industries were innovating through 3D solid and parametric modelling, building construction industry drawings were being created manually in the same way as had previously been done with pencil and drawing board.

To overcome the limitations of CAD, there has been a need for new pioneering technologies and innovative design processes. As a result, Building Information Modelling (BIM) has emerged as a 'fresh look at information flows and communication in building design and construction' (Demian & Walters, 2014). BIM consists of object-based models that not only represent the geometric data of projects (2D and 3D) but also their non-geometric information including 4D (integration of the BIM with schedule), 5D (quantity extraction from the BIM) and 6D (use of the BIM in facilities management) (Harvard University Construction Management Council, n.d.). It extends beyond the capabilities of CAD, since its elements have intelligent relationships between each other. In addition, each element has a high level of information attached to it, such as, object type (.i.e. window, door, column, roof), name, materials and object identification (ID) number (Zhang et al., 2013).

These advances have led to a great deal of interest in BIM among academics, governments and professionals. In 2011, unlike many other countries, the UK Government Construction Strategy (GCS) required Level 2 BIM - based on a BIM maturity model - for all publicly funded projects by 2016 (Ngo, 2012). The BIM maturity model includes evolutionary levels ranging from Level 0 where CAD is applied, to Level 3 Integrated BIM (iBIM) (Figure 1). A BIM Task Group was initiated to support deliver the objectives and the target of BIM Level 2 by 2016. Since the release of the Government's strategy, there has been a wider spread of awareness and implementation of BIM in the UK. According to the National BIM Report 2016, 54% of the UK's AEC industry is aware and currently using BIM compared to only 13% using BIM, 45% were just aware of it in 2011 (RIBA Enterprises, 2016). In the 'Digital Built Britain', and as a result of this implementation, BIM has been identified as 'a significant contributor to the savings of £804m in construction costs in 2013/2014' (HM Government, 2015).

Influenced by the UK's initiative, an EU BIM Task Group was created in 2016 to encourage the common use of BIM as a 'digital construction, in public works with the common aim of improving value for public money, quality of the public estate and for the sustainable competitiveness of industry' (EU BIM Task Group, 2016).

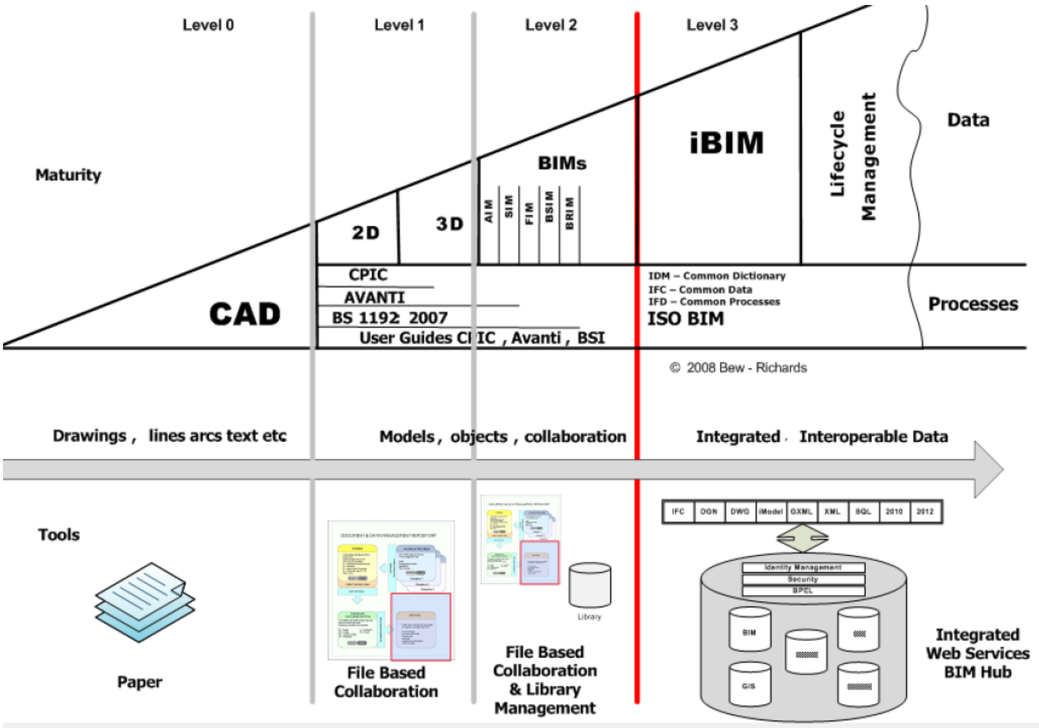


Figure 1 BIM Maturity Model (BIM Industry Working Group, 2011)

In academia, a large number of studies has focused on BIM, in particular, exploring its advantages and opportunities (Migilinskas et al., 2013; Sanchez et al., 2016). Research has found that BIM has the potential to enable significant savings of time (Popov et al., 2010) and cost (Gilkinson et al., 2014), improve collaboration between stakeholders (Bryde et al., 2013), offer a key communication tool throughout the project life cycle (Gómez-Romero et al., 2015) and increase efficiency, quality and productivity in the construction industry (Arayici et al., 2011). So powerful and positive are these benefits that made some researchers consider BIM as one of the most promising recent phenomena in the AEC sector (Azhar, 2011), a powerful technology (Yan & Damian, 2008) and an approach that is fundamentally shaping the process of designing and constructing projects (Giel et al., 2010).

To investigate whether BIM's implementation is successful, and to observe how BIM is being used in practice, a series of BIM Assessment Methods (BIM-AMs) have emerged. Since 2007, there have been at least sixteen BIM-AMs developed, both by academics and AEC businesses. Frameworks and methods, such as the National BIM Standard Capability Maturity Model (NBIMS-CMM) (NIBS, 2007) and the Arup's BIM Maturity Measure (BIM-MM), have provided different perspectives on BIM performance measurement. Individually and collectively, BIM-AMs have contributed significantly to the growing literature of performance measurement, but the field as a whole still faces multiple challenges such as a lack of implementation in practice and a high level of dependency on qualitative measures. This thesis contributes to this growing research field by exploring the current perspectives and suggesting future directions of BIM-AMs.

1.1 Background: Building Information Modelling

There has been a heated debate about whether BIM is a technology or a sociology (Harvard UCMC, 2013), modelling or management (Race, 2012), an evolution (Yan & Damian, 2008) or a revolution (Azhar et al., 2012; Hackett, 2016). Even the acronym itself is interpreted differently .i.e. BIM refers to Building Information Modelling, Building Information Model and Building Information Management, as in Figure 2. It is extraordinary that whilst there is no shortage of publications about BIM, its definition is still under-explored, provoking significant disagreement on what BIM actually is. 'BIM means different things to different people and in different contexts' (Demian & Walters, 2014). It is an umbrella term for a growing list of areas and sub-areas ranging from, but not limited to, technologies, tools and techniques to processes, standards and guidelines.

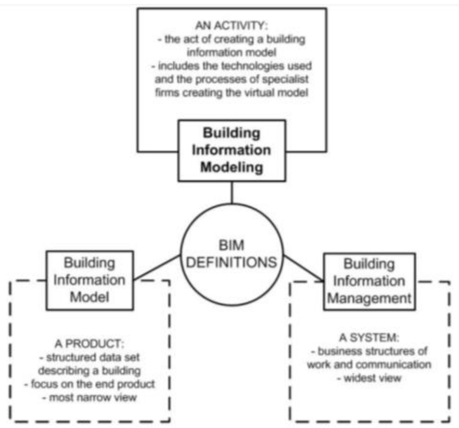


Figure 2 BIM definitions. Source (NIBS, 2007) as cited in (Ahmad, 2014)

One way to better understand the growing phenomena of BIM is to investigate frameworks that try to draw its boundaries. Table 1 presents some of the popular definitions of BIM introduced by academics, governments and industry organisations.

Table 1 Popular definitions of BIM

Reference	Definition
(BIM Task Group, 2013)	A collaboration approach throughout the asset's life-cycle. This collaboration is underpinned by the development and exchange of shared 3D models which contain structured and intelligent objects.
(HM Government, 2015)	A collaborative way of working where digital technologies are used to achieve 'more efficient methods of designing, creating and maintaining' projects. This could be achieved by creating a 3D computer model to use throughout the project lifecycle for effective information management.
(AUTODESK, 2014)	A process of building and using an intelligent 3D model to enhance and communicate the decisions of the project. BIM enables greater levels of clarity for all stakeholders and enhances collaboration, visualisation and simulation. BIM makes it easier to achieve project and business goals.
(CIC, 2013)	'A process focused on the development, use and transfer of a digital information model of a building project to improve the design, constructions and operations of a project or portfolios of facilities'.
(HUCMC, n.d.)	BIM consists of intelligent 3D objects which understand the relationships and properties of other elements. Consequently, BIM is comprised of visual representation and database of a building. As a term, BIM refers to both Building Information Modelling (the process of creating and using the model) and to Building Information Model.

Amongst the most recognised and widely cited definitions of BIM in the literature are the definitions provided by the National Institute of Building Sciences (NIBS) and Succar and Kassem (2015). According to NIBS, BIM is the digital representation of the physical and functional characteristics of a facility. It provides a reliable and shared source of information knowledge that inform decisions throughout the project life-cycle (NIBS, 2007). BIM is most clearly understood by the definition of Succar and Kassem (2015) who argue that BIM is ‘the current expression of construction industry innovation, a set of technologies, processes, and policies, affecting industry’s deliverables, relationships and roles. This multi-dimensional view of BIM offers a more comprehensive and a more integrated way of understanding BIM by combining its scattered elements rather than focusing solely on its fractional elements. The main difference between these two definitions is their focus. Whilst the first emphasises on the technology part of BIM, the latter addresses the multi-faceted aspects of BIM and structures them in three main areas and multiple sub-areas (Figure 3).

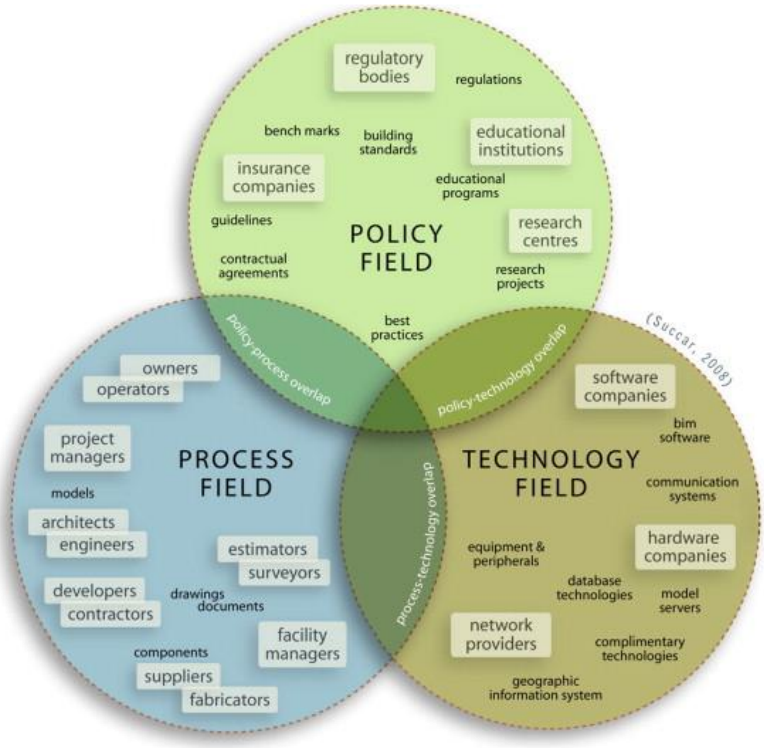


Figure 3 BIM definition

The diverse and contrasted views of BIM and its definitions illustrate the rapid growth of this research topic and the confusion surrounding the ‘ill-defined’ acronym (Succar et al., 2012). Individuals from different disciplines, such as, architects, structural, mechanical and electrical engineers, might define BIM differently according to their own perspectives, experiences, roles and BIM engagement in academia and (or) AEC industry. Creating a shared perspective on what constitutes BIM is crucial to minimise the confusion in literature of BIM definition.

1.2 Problem statement

Research into performance measurement is not a new phenomenon. For over a century, there has been an interest in performance measurement systems in diverse research fields, including, business management, software engineering and the sustainable built environment (Bititci et al., 2012). In discussing the 'revolution' of business performance measurement, Neely (1999), one of the major authors in this field, highlights eight reasons for the increasing need for Assessment Methods (AMs). These reasons are:

> "The changing nature of work, increasing competition, specific improvement initiatives, national and international quality awards, changing organisational roles, changing external demands, and the power of information technology."

Similar reasons impacting businesses in the AEC industry have led to the initiative of at least sixteen BIM-AMs both in academia and industry. Since 2007, there has been a significant research directed towards BIM performance measurement. Exiting BIM-AMs, which have different levels of similarities and differences, have all added value to the field of BIM performance and provided businesses with multiple measurement perspectives.

Yet obstacles stand in the way of BIM-AMs evolution. Despite the growing interest, the field as a whole is still lagging behind when compared to other research disciplines, such as building environmental AMs (Kam et al., 2013b). Researchers of BIM-AMs have focused on introducing their own new models, but most have failed to bring together this extensive body of knowledge as a robust whole. Only a handful of researchers have applied their models in practice, which is essential to shift the field of BIM-AMs from its theoretical basis into an effective and practical context. Finally, the credibility and consistency of most existing AMs are not well understood, since they are built on qualitative measures that are subjective and rely on assessor's opinion. Therefore, different assessors of the same project might generate completely different outcomes.

1.3 Research justification

It has been recognised that AMs have the potential to move companies forward (Kaplan & Norton, 2005). AMs reflect companies' missions and strategies, address current and future successes and assist businesses to focus their priorities and communicate their goals across all the organisational levels (Kaplan & Norton, 2004). They have, therefore, gained considerable popularity and have wide spread development and implementation across various research fields (Bourne et al., 2000; Haapio & Viitaniemi, 2008).

In recent years, the potential of AMs has become increasingly recognised in the BIM domain by academics, professionals and policy makers. For academics, the application of BIM-AMs can shed light on how BIM is being implemented in practice an. For professionals, assessments can be used by managers for different purposes; to evaluate BIM's benefits (Barlish & Sullivan, 2012), assess their BIM performance, strengths and weaknesses (Succar, 2010a) and suggest actionable recommendations of the BIM implementation process. For policy-makers, and with UK's 2016 BIM strategy, AMs can help identifying businesses' capabilities and their ability to meet certain BIM levels of maturity. Furthermore, the implementation of AMs can also be beneficial in providing an overall picture of current levels of BIM utilisation, internally in an organisation, nationally within a country and internationally across different countries. A further detailed explanation of the need for assessments and their importance is discussed in Chapter 3.

1.4 Initial aim and Objectives

The initial aim of this thesis was to understand and demonstrate the possible ways to evaluate BIM including its evolving policies, technologies and processes. To achieve this aim, the following objectives were undertaken:

1- To review the development of performance measurement systems in different research fields. This would help to learn lessons and to understand the history of performance measurement; its opportunities and challenges.
2- To provide an overall view of the development of BIM-AMs in the last decade; their evolution, definitions, benefits and challenges.
3- To apply multiple BIM-AMs in practice to observe their potential and limitations.

1.5 Thesis outline

This thesis consists of nine chapters. In Chapter 2, a comprehensive literature on AMs in different research fields is discussed prior to Chapter 3 which focuses on AMs in the BIM domain. Together, the two chapters provide the state of the art of AMs and cover a wide range of areas including the definitions, evolution, research types, roles and limitations, and instances of AMs. Chapter 3 ends with an explanation of how BIM-AMs have been influenced and shaped by AMs in different research fields. In Chapter 4, the research methods to achieve the research aim and objectives are explained.

Chapter 5 gives a critical comparison of existing AMs, which brings together the research agenda of BIM-AMs as a coherent whole. The implementation of AMs in practice, the design process of assessments, the range of measures and the assessment's focus are amongst the investigated themes of the chapter.

In Chapters 6 and 7, multiple AMs are applied in the UK's AEC industry. A pilot testing approach is undertaken in Chapter 6 to explore the practicality and validity of AMs, their opportunities and challenges in practice. In Chapter 7, a more comprehensive and detailed case study is applied in association with Arup; a global consulting engineering firm. The testing in the latter chapter is divided into two rounds, to investigate the relationship between the assessor's experience and the outcome of the AMs.

Chapter 8 introduces an approach to automate the process of BIM measurement. Finally, overall remarks are concluded in Chapter 9, which outlines limitations of the research and suggests future directions of the AMs' research field. The structure of this thesis is presented in a table at the start of each of the following chapters.

2 Literature Review: Performance measurement

Chapter 2 provides a comprehensive review of performance measurement literature. The definitions, history, design process and the desirable characterisations of performance measurement systems are introduced and analysed prior to investigating the BIM-AMs in Chapter 3.

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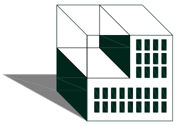		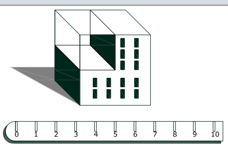
Main questions included: What is BIM? What is the need for BIM-AMs?	Includes: - Brief history of the broad PMSs, their definitions - PMSs roles and barriers - Sample of PMSs	- Explains the wide range of BIM-AMs, their evolution, opportunities and challenges - Investigates how BIM-AMs have been informed by the broader PMSs
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	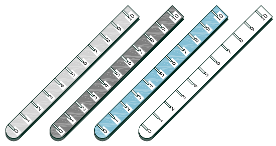	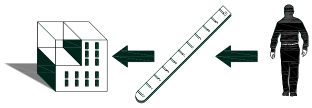
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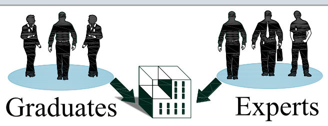
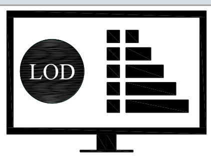
		
In association with Arup, applying three AMs to the same project and completed by six participants who have different BIM experience i.e. experts and graduates	Includes: - The need for automated AMs - The implementations of BIM-AM in practice	Current perspectives and future directions of BIM-AMs

2.1 Definitions of Performance Measurement Systems

The definition of Performance Measurement Systems (PMSs) has been discussed in many previous studies in the reviewed literature e.g. (Atkinson et al., 1997; Cole, 2005). Some of the available definitions are:

- PMSs are models that evaluate the capabilities and competencies of a selected domain against a set of desired measurement criteria (De Bruin et al., 2005).
- PMS is the regular evaluation of the efficiency and outcomes of programmes or services (Hatry, 2006).
- Assessing the way organisations are managed and evaluating how they deliver their values to customers and other stakeholders (Moullin, 2007).
- PMS is an approach to optimise processes, capabilities and business process management of an organisation. It consists of stages of maturation which help businesses identify future desirable maturity levels (Röglinger et al., 2012).
- PMS is the official recognition of an organisation when able to perform particular tasks, processes and activities in an accurate, reliable and credible fashion (UKAS, 2014).

One of the widely recognised definitions, however, considers performance measurement as the process of quantifying the effectiveness and the efficiency of an action, whilst PMS is the criteria of measures applied to quantify the effectiveness and the efficiency of actions (Neely et al., 1995). Management teams can implement PMSs to identify the critical questions which they have to address when managing their businesses (Neely et al., 2001).

The varied definitions of PMSs reflect the diversity of this topic and the lack of clarity of defining their characterisations and components. All definitions, however, reflect one or a combination of three elements i.e. the features of the assessment, the roles it plays and, or the processes that are taking part in the assessment (Bourne et al., 2007). Linking these three elements together might help to provide a more robust, more coherent and a clearer picture of this field.

2.2 Why measure performance?

Questioning why to measure performance has been the subject of various novel studies in the last couple of decades. The evolving nature of businesses, growing competition and the changing business roles (amongst other reasons) have all led to a ‘revolution’ of PMSs throughout the 1990s (Neely, 1999). Behn (2003) observes that there are eight purposes for measuring performance:

> "As part of their overall management strategy, public managers can use performance measures to evaluate, control, budget, motivate, promote, celebrate, learn and improve." (Behn, 2003)

Behn (2003) suggests that businesses can benefit from PMSs for different reasons, and measures must reflect these varied reasons also. Similarly, various researchers have explicitly documented the need for PMSs and their vital importance for organisations. Some of the notable instances are exhibited in the following:

- Provide a top-down reflection of organisation's strategy by enabling companies to communicate high-level goals and priorities down to all businesses' levels (Kaplan & Norton, 2004).
- A balanced scorecard combines various 'desperate elements' of a business' agenda in a single management report. This report, in turn, will assist organisations in improving quality, focusing on teamwork, managing their long-term plans and becoming customer oriented (Kaplan & Norton, 2005).
- Help businesses to identify where they are, to track the speed of their improvement and to allow comparison with other companies (Neely et al., 1997).
- Help organisations to answer five critical questions: where they have been? Where they are currently? Where they want to go? How they are going to get there? And how to know they are there? (Lebas, 1995).
- Play a significant role in initiating strategic plans and assessing the achievement of organisational objectives (Ittner & Larcker, 1998).
- Help organisations to identify success, investigate bottlenecks and ensure that decisions are built on facts, not on emotion or supposition (Parker, 2000).
- By structuring the domain's criteria in an organised framework, assessments can create a common language between the different teams which helps to enhance a strategic dialogue (Cole, 2006).
- In manufacturing, an appropriate PMS is one of the key ingredients for organisations to be classified as world class (Medori & Steeple, 2000).
- For governments, PMSs provides higher levels of confidence in the consistency and competence of activities across all market sectors.

There is, therefore, a wide range of benefits of PMSs which explain the broad interest in the field of performance measurement in different disciplines. They are seen to enable companies to communicate objectives, assess domain capabilities at different phases and allow comparisons against a range of competitors (De Bruin et al., 2005). As a result, professionals, policy-makers and academics have a greater understanding of existing domain capabilities, what current opportunities and challenges are and how they are likely to evolve in future.

2.3 History of performance measurement

The last century has witnessed a remarkable development in the field of performance measurement, rooted in early accounting systems (Bourne et al., 2003). In the early 1900s, there was enormous emphasis on financial measures, namely, productivity management (Bititci et al., 2012), profit, return on investment (Ghalayini et al., 1997) and budgetary control (Kashyap & Wilcox, 1993). Such control systems were broadly implemented but rarely evolved throughout the following 80 years (Neely & Bourne, 2000). Figure 4 illustrates a brief history of this field since 1900 and identifies the main emerging themes. This includes the emergence of PMSs in public sector and non-profit organisations in different disciplines.

In the 1980s and early 1990s there was an ‘explosion’ in the number of publications criticising past PMSs for being focused only on financial measures (Neely et al., 2003). ‘Traditional’ PMSs were criticised for providing ‘misleading signals’ for constant improvement (Kaplan & Norton, 2005), measuring only the short-term financial performance results (Kaplan & Norton, 1995) and being inadequate to manage and assess evolving businesses. Indeed, internal and external business environments had changed but PMSs had not kept up, which is crucial to maintain relevant and appropriate measures that reflect the most critical issues of businesses. Based on these observations, researchers and professionals started to realise that relying solely on financial measures was ‘not enough’ to evaluate whether businesses were meeting their goals successfully or not (Institute of Chartered Accountants of Scotland, 1993).

As a result, in the late 1980s and early 1990s there was a desire to quantify and track new measures, such as internal operations performance and customer satisfaction. Most of these attempts, however, evaluated these emerging measures individually and not in an integrated manner (Neely & Bourne, 2000). In order to improve these attempts, PMSs research shifted towards ‘performance measurement frameworks’. Researchers, therefore, combined traditional financial measures with non-financial ones and introduced them into comprehensive measurement frameworks (Neely, 2005).

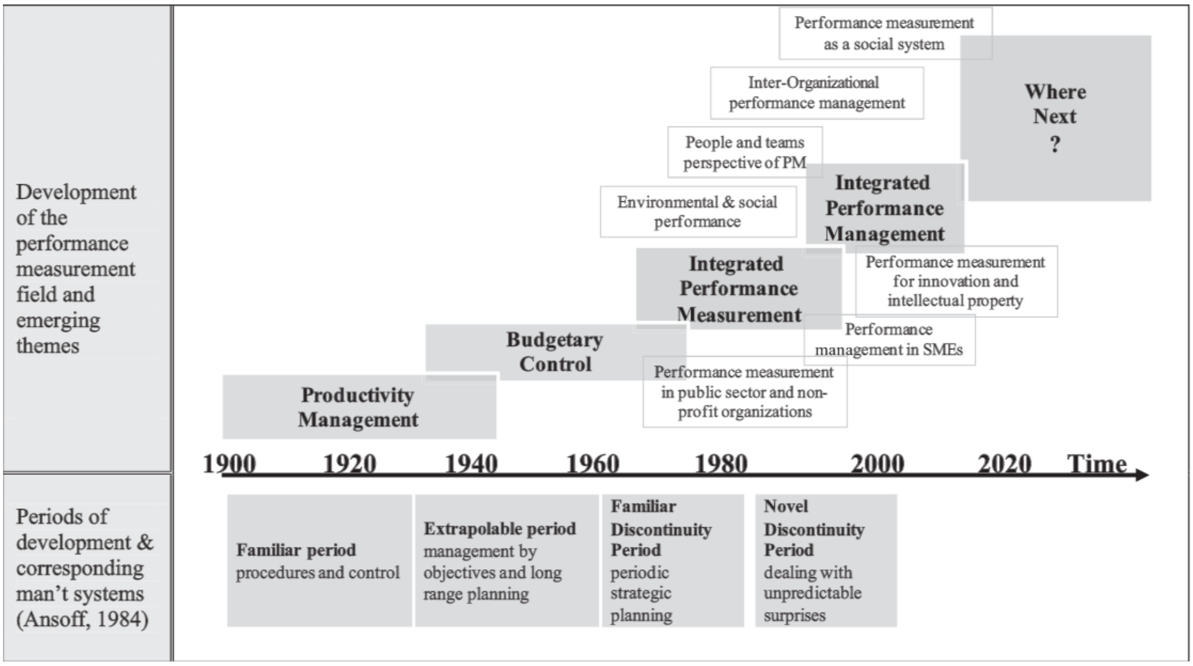


Figure 4 The development of performance measurement literature (Bititci et al., 2012)

Instances of integrated frameworks are the Performance Pyramid, Figure 5, (Lynch & Cross, 1991), The Performance Measurement Matrix, Figure 6, (Keegan et al., 1989) and the Balanced Scorecard (BS) (Kaplan & Norton, 1996b). These novel models have been widely researched and adopted in practice, (Gibbons & Kaplan, 2015; Hoque, 2014; Hunt et al., 2016), since they provided new approaches with integrated systems, rather than focusing one facet. The strength of such models lies in combining internal and external, financial and non-financial measures. The link between the varied dimensions of each framework is varied and seems to be highest in the BS, which is one of its key strengths (Neely et al., 2000).

The 'maturation' of performance measurement research, as a whole, can be better understood by grouping its literature according to their various categories. This includes their nature, target, scope, assessment objectivity (Cole, 2006), range of measures and the forms of results used (Haapio & Viitaniemi, 2008). A broader classification approach of PMSs builds on their overall features, limitations and areas of optimisation. In other words, three 'generations' of PMSs are introduced (Neely et al., 2003):

1. The first generation: balanced measurement systems.
2. The second generation: mapping the flows and transformations.
3. The third generation: linking the financial to non-financial.

Collectively, these generations provide a brief snapshot of the maturation of PMSs. Each builds on the previous in order to avoid shortcomings and enable areas of optimisation. In the second generation, studies tend to overcome the main limitation of the first (namely, addressing only financial measures) by linking different objectives, measures and resources using strategy maps. The third generation builds on the second, but also provides businesses with the 'big picture of what is happening inside the organisation' (Neely et al., 2003).

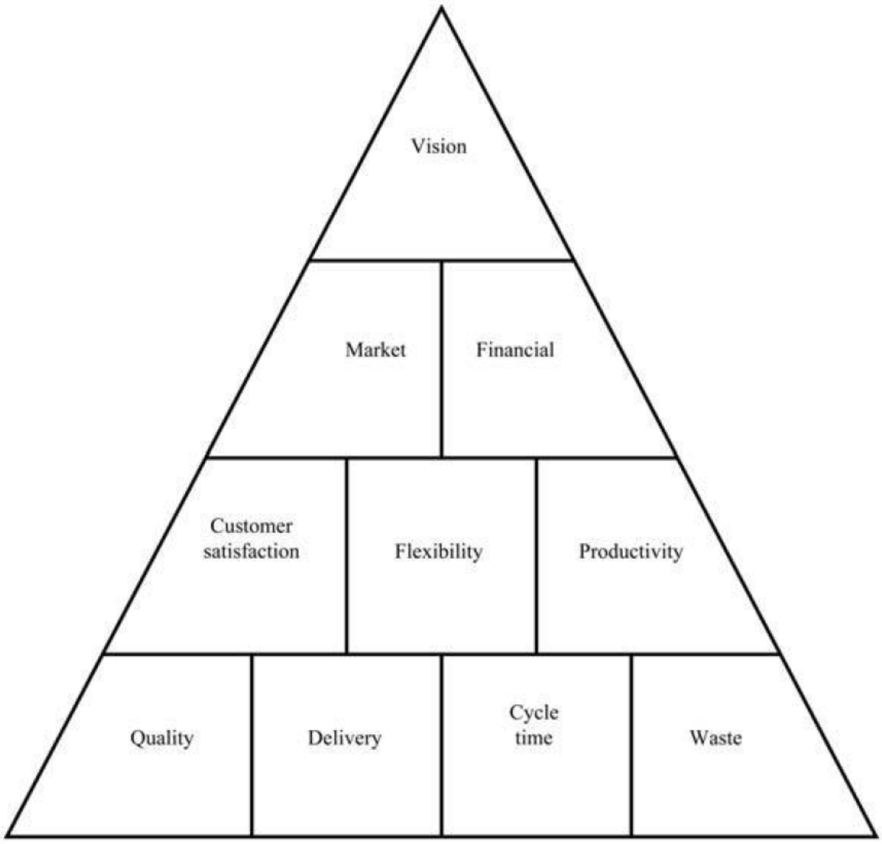


Figure 5 The Performance Pyramid (Lynch & Cross, 1991) cited in (Neely et al., 2000)

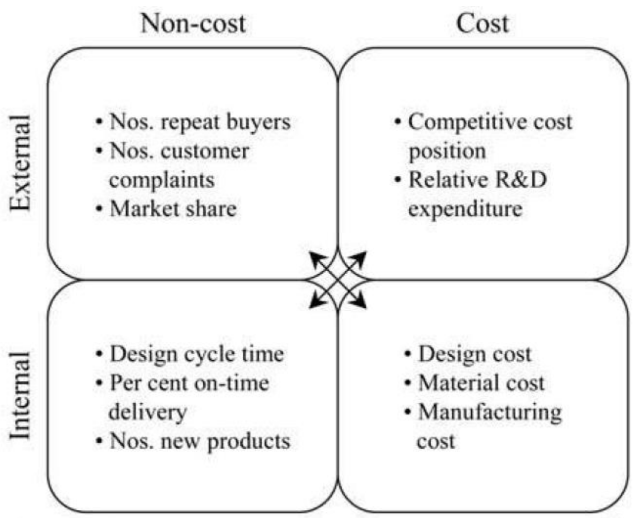


Figure 6 The Performance Measurement Matrix (Keegan et al., 1989) cited in (Neely et al., 2000)

Another way to classify the vast research of PMSs and simplify its complexity is to group current literature based on research type. PMSs research can be classified in four major groups. Firstly, studies that introduce and document new tools and models. Contributions to this group tend to provide theoretical and practical background on new emerging assessments (BREEAM, 2015; Ghalayini et al., 1997). Secondly, studies that apply assessments to real case study projects (Baraldi & Cifalinò, 2015; Neely et al., 2001). Thirdly, studies that compare and critique current AMs (Todd et al., 2001; Zeinal Hamedani & Huber, 2012). Research of this group provides a holistic view of existing models, their evolution and predicted future trends. It also explores their similar and different characteristics and examines their emerging roles, opportunities and challenges. Fourthly, there are studies that investigate the design process of PMSs (de Haas & Kleingeld, 1999; Lohman et al., 2004). This group is devoted to the question of how to structure a PMS, what research methods to apply when designing an assessment, what measures to include, and how to populate the assessment.

Having discussed the history of PMSs, the following presents two frameworks; the Balanced Scorecard and the Performance Prism Framework. These two models are chosen for further study due to their significant contribution to the field of performance measurement. The developers of both models are some of the most prolific authors in the PMSs research field.

2.3.1 The Balanced Scorecard

The Balanced Scorecard (BS) is perhaps the 'best known' performance measurement framework (Neely et al., 2005). The BS is a framework that consists of a set of measures providing top managers with a fast and yet overarching picture of the business (Kaplan & Norton, 2005). It assesses organisations across four "balanced perspectives" (Kaplan & Norton, 1996a), as seen in Figure 7.

The scorecard has been broadly adopted by non-profit organisations, service and manufacturing companies and government entities (Kaplan & Norton, 2001). It was firstly introduced in 1992 by Robert S. Kaplan and David P. Norton at Harvard University. Since then, it has generated intense research attention and enormous industrial consideration. For instance, an extensive analysis of literature investigated PMSs research, and found that studies published by Kaplan and Norton were the most cited for eight years between 1995 and 2004 (Neely, 2005). Their wide recognition and influence is still remarkable to date, two decades after its initial development (Hoque, 2014).

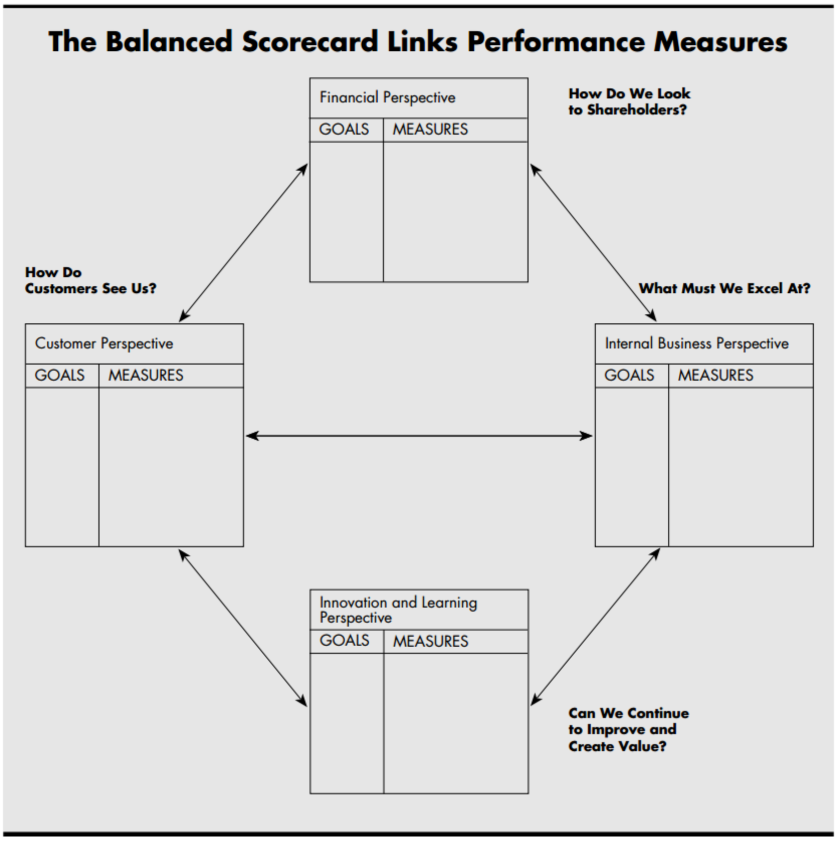


Figure 7 The Balanced Scorecard (Kaplan & Norton, 2005)

In their initial publications on the BS, Kaplan and Norton directed little attention towards the design process of the scorecard (Neely et al., 2000). Later, they recognised the necessity of this process and introduced a six-step process which each organisation has to use when building their own unique scorecard (Kaplan & Norton, 1995). These stages are preparation, interviews (first round), executive workshop (first round), interviews (second round), executive workshop (second round) and executive workshop (third round). This process enables organisations to identify the most critical fifteen to twenty measures to track across the four perspectives (meaning four to five measures in each perspective).

Undoubtedly, the BS is the most popular performance measurement framework (Neely et al., 2001). Despite the popularity and publicity surrounding the scorecard in both academia and practice, many limitations have been noted in the literature. It was criticised for being a controlling and tracking framework rather than an improvement tool (Ghalayini et al., 1997), downplaying the importance of some stakeholders, including employees and suppliers (Neely & Adams, 2000) and also for being inadequate in different circumstances and across organisation types (Maltz et al., 2003). Moreover, the developers of the scorecard provided little guidance for businesses to help them identifying their measures (Neely et al., 2000). Companies are left to find their performance measures without sufficient guidance on how to select and measure them (Tangen, 2004). These limitations have led to the emergence of new models and tools, such as the Performance Prism.

2.3.2 The Performance Prism Framework

The Performance Prism is a scorecard that manages and measures business success (Neely et al., 2002). It has been examined in practice with available case studies in the House of Fraser, DHL and London Youth (Neely et al., 2001). The developers of the Performance Prism believe that the best way for businesses to 'survive' long-term is to carefully think about the needs and the wants of their stakeholders. By doing so, this will allow organisations to deliver appropriate value to each stakeholder. This is reflected in five interrelated facets of the 'Performance Prism'; each aims to answer one fundamental question. These facets are (Figure 8):

1. Stakeholder satisfaction: who are the stakeholders, what do they want and need? Stakeholders here might include intermediaries, suppliers, customers, employees, alliance partners, investors and or local community.
2. Stakeholder contribution: what do we want and need from our stakeholders? This means that organisations have to understand the two-way 'relationship' with their stakeholders.
3. Strategies: what are the needed strategies to reflect these wants and needs? This stage includes defining strategies built on stakeholders' needs and wants.
4. Processes: what are the processes needed to satisfy these wants and needs? The processes here include the development of new products and services, the fulfilment of demands, in addition to planning and managing enterprise.
5. Capabilities: what capabilities are needed to apply processes effectively and efficiently? Capabilities are the combination of people, technology, practices and infrastructure. Organisations have to identify the appropriate capabilities in order to be able to improve processes and compete with other businesses.

Collectively, these viewports reflect the multi-dimensional conceptualisation of organisations' management and performance. By addressing these five questions, organisations are able to build overarching success maps for what is important for them (Neely et al., 2003). Similar to BS, the Performance Prism extends beyond traditional financial measures. It is claimed that this framework, however, provides a much more overarching approach compared to other frameworks, since it directs attention towards wider stakeholders (Tangen, 2004).

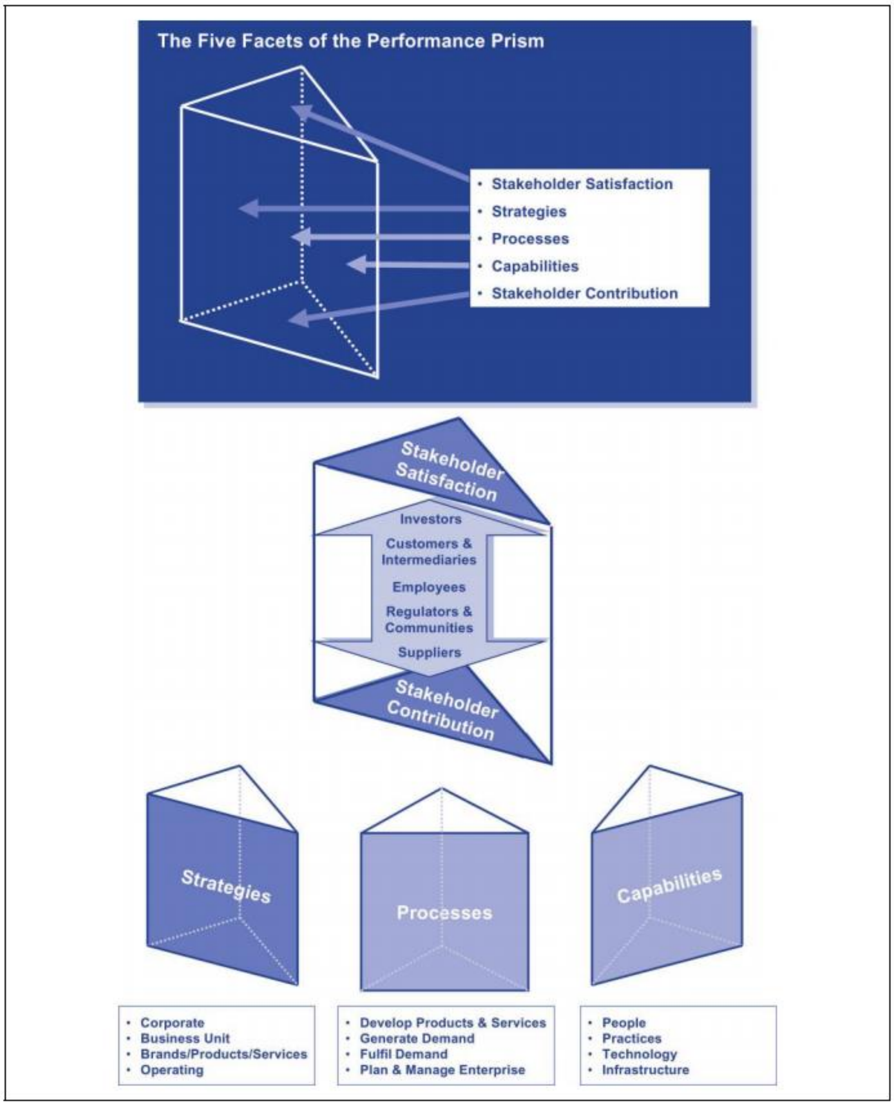


Figure 8 The Performance Prism Framework (Neely et al., 2001)

2.3.3 Summary

Both the BS and the Performance Prism offer a dynamic and flexible approach to measuring performance. They have solved many shortcomings of traditional financial measures. For instance, these models attempt to limit the number of chosen measures to diminish information overload. They have also provided businesses with strategically-driven frameworks (Tangen, 2004). However, applying them in practice requires businesses to identify what needs to be measured built on the organisation's strategy in the BS and on the stakeholders' wants and needs in the Performance Prism. Companies, therefore, can create their own models. Their main challenge is to realise which measures to include and how to track these measures. This open-ended approach is beneficial allowing each organisation to adjust the framework to their own a unique case. However, as a result, this makes it difficult to enable comparisons across other organisations.

Having discussed the history of PMSs, and illustrated two of their models, the following will demonstrate two branches of this field. The first is the building environmental AMs for their relevance to the built environment domain and the second is the development of Capability Maturity Models (CMMSs), in particular, in software engineering. Both fields are crucial because of their impact and influence on the development of BIM-AMs.

2.4 Building environmental AMs

Building environmental AMs are frameworks that evaluate buildings against a broad range of environmental performance measures. Their main aim is to document and induce ‘progress’ towards a more sustainable built environment (Schweber, 2013). Environmental assessments have had significant attention from governments, policy-makers and academics (Schweber & Haroglu, 2014). The development of this field has matured significantly since the early 1990s with the release of the UK’s Building Research Establishment Environmental Assessment Method (BREEAM) (Cole, 2005). Since then a vast number of AMs has been developed internationally, including the Leadership in Energy and Environmental Design, operated by the US Green Building Council, the Hong Kong Building Environmental Assessment Method (HK-BEAM), Green Star from Australia and the Comprehensive Assessment System for Built Environment Efficiency (CASBEE) from Japan. These models have contributed individually and collectively to the knowledge surrounding this research field, since each has its unique focus, characteristics and agenda.

The environmental AMs literature directs great attention towards comparing, contrasting and critiquing existing AMs, much more than developing new methods. This is exemplified in the work of Raymond Cole at the University of British Columbia who is one of the leading researchers in this field. In his studies Cole explores the emerging trends of building environmental AMs (Cole, 1998) and the use of BREEAM and LEED internationally (Cole & Jose Valdebenito, 2013). He examines available AMs in terms of their definitions, roles, evolution, content and limitations. Similar approaches can also be found in the work of Ding (2008), Haapio and Viitaniemi (2008), Sharifi and Murayama (2013) and Crawley and Aho (1999), who comprehensively review and analyse the properties of twenty, sixteen, seven and four AMs respectively. These studies are crucial to identifying the research agenda of environmental AMs and to highlight areas of convergence and distinction. Since BREEAM is one of the ‘best established’ environmental AMs (Schweber, 2013), it is presented in the following.

In 1990, the Building Research Establishment (BRE) introduced BREEAM, which was the first overarching AM to be explicitly directed at evaluating buildings (Cole, 2005). It is described as one of the most successful environmental assessments, at least in regards to uptake, with more than 15000 certified buildings since its release in 1990, half of them since 2008 (Schweber & Haroglu, 2014).

This voluntary assessment addresses ten environmental categories: energy, health and wellbeing, innovation, land use, materials, management, pollution, transport, waste and water. Versions of BREEAM have been developed to assess both new and existing buildings (Crawley & Aho, 1999). Like other AM, such as LEED, CASBEE and Green Star, the process of assessment in BREEAM is carried out by a third-party licensed assessor (Figure 9). When a building is assessed, a single score is calculated and allocated to one of five levels, namely, Pass, Good, Very Good, Excellent and Outstanding.

For over two decades, BREEAM have been broadly implemented in the UK. However, during this period, it has been adapted and changed. The earliest version of BREEAM was designed to assess the environmental performance of offices. In later years, new schemes emerged to evaluate different types of buildings, such as, schools, housing and hospitals (Saunders, 2008). Furthermore, the initial aim of its development was to assess buildings and communicate environmental quality of projects to the property market and public.

In the past decade, however, BREEAM has moved beyond its primary aim. Both policy-makers and the BRE have viewed it as not only an AM but more importantly as a 'design tool' (Schweber & Haroglu, 2014). Since BREEAM evaluates a wide range of environmental criteria, it is possible, therefore, to use these criteria to communicate the most crucial environmental considerations to different stakeholders, including building owners and design teams (Cole, 2005). Moreover, BREEAM was initially developed as a voluntary assessment, but since 2000 it has shifted to be recommended by policy-makers for use, and also to be adopted in all government procurement as a 'mandatory mechanism' (Schweber, 2013).

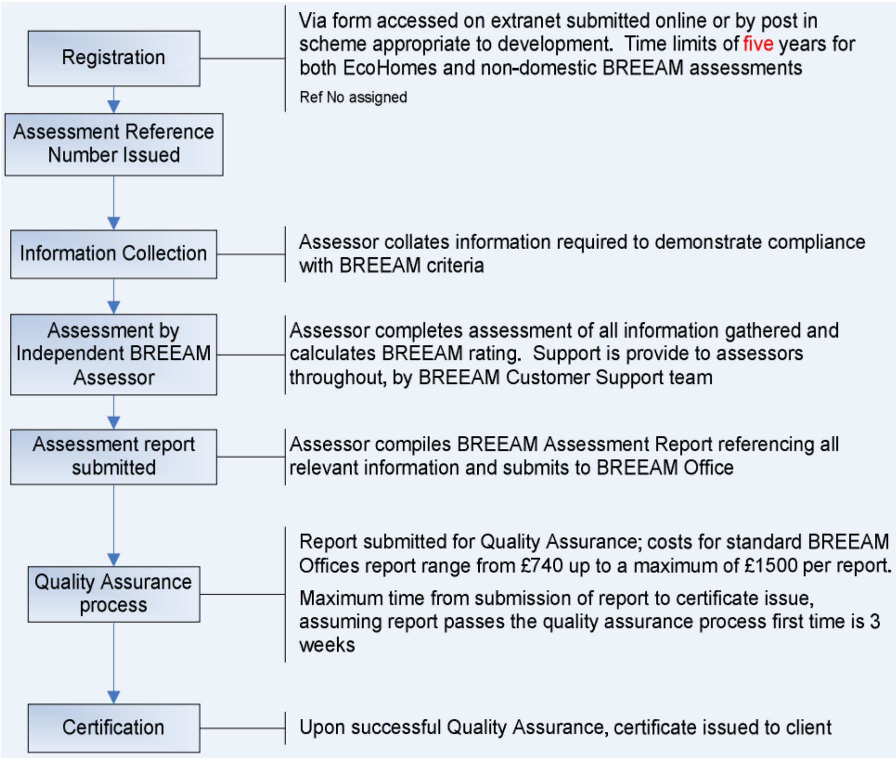


Figure 9 BREEAM third party verification process (Saunders, 2008)

2.5 Capability Maturity Models (CMM(s))

One branch of AMs is concerned with the development of Capability Maturity Models (CMMs) which is originated in quality management research (Crosby, 1979). The CMM is a framework that reflects a 'path of improvements' for organisations who want to improve their process capabilities (Paulk et al., 1993). The purpose of a structured assessment is to set direction, prioritise tasks and initiate a cultural change. Repeating the assessment is of vital importance as it helps organisations to check their current progress and establish the following logical steps forward (Crawford, 2007).

The most popular approach to evaluate maturity is five (sometimes six) 'levels of maturity' identified to reflect the increasing maturity (De Bruin et al., 2005). Maturity levels draw on the concept that each process has a life-cycle and that the completeness of the life-cycle should be assessed (Lockamy III & McCormack, 2004). Higher maturity levels build on the requirements of the lower ones. Such levels are crucial to evaluating the capability growth, consistency and richness of processes amongst the organisation as a whole (Thayer et al., 1997). Existing CMMs apply similar approaches to define 'levels of maturity'. A sample of these levels is presented in

Table 2. Similar approaches have been observed in the BIM literature and will be discussed in Section 5.6.

Table 2 Maturity levels. Source: (Succar et al., 2012)

MATURITY MODELS	Maturity levels					
COBIT, Control objects for information and related technology	Non-existent	Initial/ad hoc	Repeatable but intuitive	Defined process	Managed & measurable	Optimized
CMMI, Capability maturity model integration (staged representation)		Initial	Managed	Defined	Quantitatively managed	Optimizing
CMMI (continuous representation)	Incomplete	Performed	Managed	Defined	Quantitatively managed	Optimizing
CSCMM, Construction supply chain maturity model		Ad-hoc	Defined	Managed	Controlled	N/A
LESAT, Lean enterprise self-assessment tool		Awareness/Sporadic	General awareness/informal	Systemic approach	Ongoing refinement	Exceptional/innovative
P-CMM®, People capability maturity model		Initial	Managed	Defined	Predictable	Optimizing
P3M3, Portfolio, programme and project management maturity model		Awareness	Repeatable	Defined	Managed	Optimized
$(PM)^2$, Project management process maturity model		Ad-hoc	Planned	Managed at project level	Managed at corporate level	Continuous learning
SPICE, Standardized process improvement for construction enterprises		Initial/chaotic	Planned & tracked	Well defined	Quantitatively controlled	Continuously improving
Supply chain management process maturity model		Ad hoc	Defined	Linked	Integrated	Extended

2.5.1 Software CMM

The research field of BIM-AMs has been continuously influenced by the development of CMMs, in particular the CMM for software engineering management (Giel, 2013; Succar et al., 2012). Initially released in 1991, then reviewed and used in 1992 (Paulk et al., 1993), the software CMM was developed to place emphasis on processes as a crucial element in organisational and project success. This CMM was developed by the Software Engineering Institute (SEI) at Carnegie Mellon University and funded by the Department of Defence. Similar to other CMMs, this model consists of five evolutionary maturity levels and each reflects a level of software process capability. These levels are well defined by the SEI where higher levels suggest more improved processes than the lower ones.

There are diverse uses of this CMM, for example (Paulk, 2002):

1. The CMM can be used by assessment teams to identify areas of strengths and weaknesses in an organisation.
2. Enables staff and managers to understand the activities needed to plan and adopt software process improvement in their organisation.
3. Can be used by process improvement groups as guidance.
4. Allows software organisations to optimise their software process capabilities.

Initial studies on CMMs can be found in software engineering (Paulk et al., 1994), but it was then developed and adopted by different disciplines, such as supply chain management (Meng et al., 2011), business process management (McCormack et al., 2009) and project management (Crawford, 2014). Project management, in particular, has learnt how to optimise processes based on the efforts in the software industry (Crawford, 2007). The adoption of CMMs in different disciplines seems to follow a similar structure and most models tend to include simple domain-based measures to ensure continuous process improvement. The main difference between these models, however, is the domain focus and the conceptual depth.

2.6 Desirable performance measures

Despite the broad development of AMs, little research has been directed to comprehensively explore the desirable characteristics of evaluated domains. Exception can be found in the work of a few scholars including the research of Globerson (1985) who suggests guidelines for designing a performance criteria system. Based on previous studies and the Glosberson’s experience, performance criteria should be:

- Selected from the objectives of the company.
- Enables comparison across different companies.
- Should have a clear purpose.
- Use ‘ratio-based performance criteria’, rather than absolute numbers.
- Apply clearly defined research methods when collecting data.
- Managers, customers and employees should be engaged in the process when choosing the appropriate measures of the model

A later study, (Neely et al., 1997), provides a more comprehensive approach by providing a review of ten papers and books on performance measurement and lists the top 22 recommendations with regard to the design of PMSs. These recommendations are presented in order in Table 3 Desirable characterisations for performance measures (Neely et al., 1997)Table 3 according to the number of times they occur in the ten publications. These recommendations can assist researchers and professionals to explore what a ‘good’ performance measure looks like. Saying that, the desirable criteria should be based on their developers’ priorities rather than being restricted to the order suggested in Table 3. For instance, the most often observed criteria for measures in this table is to be derived from strategy. However, this could be an undesirable approach, as organisations have to start with stakeholders’ needs before developing their strategy (Neely et al., 2001).

Table 3 Desirable characterisations for performance measures (Neely et al., 1997)

1	Derived from strategy	12	Consistent
2	Simple to understand	13	Enable quick feedback
3	Offer accurate and timely feedback	14	Have explicit purpose
4	‘Should be based on quantities that can be influenced, by the user alone or in co-operation with others’	15	Reflect business process, namely, customers and suppliers should be engaged in defining measures
5	Mirror the business process	16	Use ratios rather than absolute numbers
6	Relate to particular targets	17	Use data that are automatically collected
7	Relevant	18	Communicated in a simple format
8	‘Part of a closed management loop’	19	‘Based on trends rather than snapshots’
9	Defined clearly	20	Informative
10	Provide visual impact	21	Exact and precise
11	Should focus on improvement	22	Objective –i.e. not rely on opinion

Developers of AMs should consider these recommendations as advice and as a means to learn lessons and optimise previous models. They should, however, develop their own performance criteria system according to their own research field, aims and objectives. Once these criteria are identified, further research should be carried out to investigate the design process of PMS as explained below.

2.7 The design process of PMSs

In the last couple of decades, hundreds of PMSs and maturity models have been developed. Despite this, the research methods that led to the development of these models are very often absent from the literature or documented very 'sketchily' (Becker et al., 2009). However, exceptions can be found in several comprehensive studies which highlight the design process of PMSs (Bourne et al., 2000; Lockamy III & McCormack, 2004; Pöppelbuß & Röglinger, 2011). Such studies introduce frameworks of design principles for developing a PMS. In particular they focus on the way to develop new models, what measures to include and how to communicate the outcomes. These studies offer researchers and professionals with guidelines on how to develop an assessment rather than introducing new assessments. One of these instances is the work carried out by De Bruin et al. (2005) who suggests six phases when developing a maturity assessment model. These stages are (Figure 10):

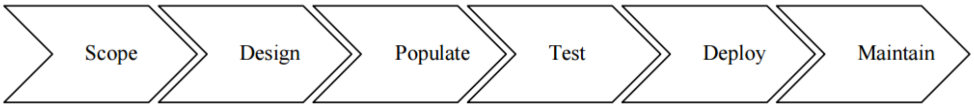


Figure 10 Main phases of developing a maturity assessment model (De Bruin et al., 2005)

1. Scope: which determines the focus of the AM (whether it is a domain specific or general), and identifies the involved stakeholders (Table 4).
2. Design: which identifies the audience, applied methods, aim of the AM, respondents and application (Table 5).
3. Populate: concerned with defining the content of the AM, what measures to choose and how to measure them. A comprehensive literature review should be investigated in order to identify domain components and sub-components. Further research methods should then be employed to validate these components, for instance using case studies, interviews, Delphi technique, focus groups and brainstorming sessions.
4. Test: this includes testing the AM to check its rigor, relevance, reliability and validity.

5. Deploy: the model in this stage should be available for use for verification and generalisation firstly by its own developers and collaborators, and secondly by independent organisations.
6. Maintain: This stage concerns the evolution of the model throughout the time. The model should be pragmatic and justifiable as the understanding and domain knowledge deepens and broadens.

Table 4 Phase 1: scope, decision when scoping a maturity model (De Bruin et al., 2005)

Criterion	**Characteristic**			
Focus of Model	**Domain Specific**		General	
Development Stakeholders	Academia	Practitioners	Government	Combination

Table 5 Phase 2: design, decision when designing a maturity model (De Bruin et al., 2005)

Criterion	**Characteristic**		
Audience	**Internal**		External
	Executives, management		Auditors, partners
Method of Application	Self-assessment	Third party assisted	Certified practitioner
Driver of application	Internal requirement	External requirement	Both
Respondents	Management	Staff	Business partners
Application	1 entity	Multiple entities/single region	Multiple entities/multiple region

Similarly, Neely et al. (2000) suggested a ‘detailed map’ that exhibits the essential ten process phases of developing a PMS (Figure 11). The principal aim of this model is to focus on design process flow of the PMS and on the employed tools and techniques at each phase. One of the interesting phases in this model, however, is in Part 6: ‘Identifying the drivers of performance’. This means that developers have to build their model based on the need for this evaluation system, which vary from case to case. By doing so, this model addresses two critical questions that developers and managers have to answer (Lebas, 1995): why to measure and what to measure? Many models would consider the latter question, but not the first.

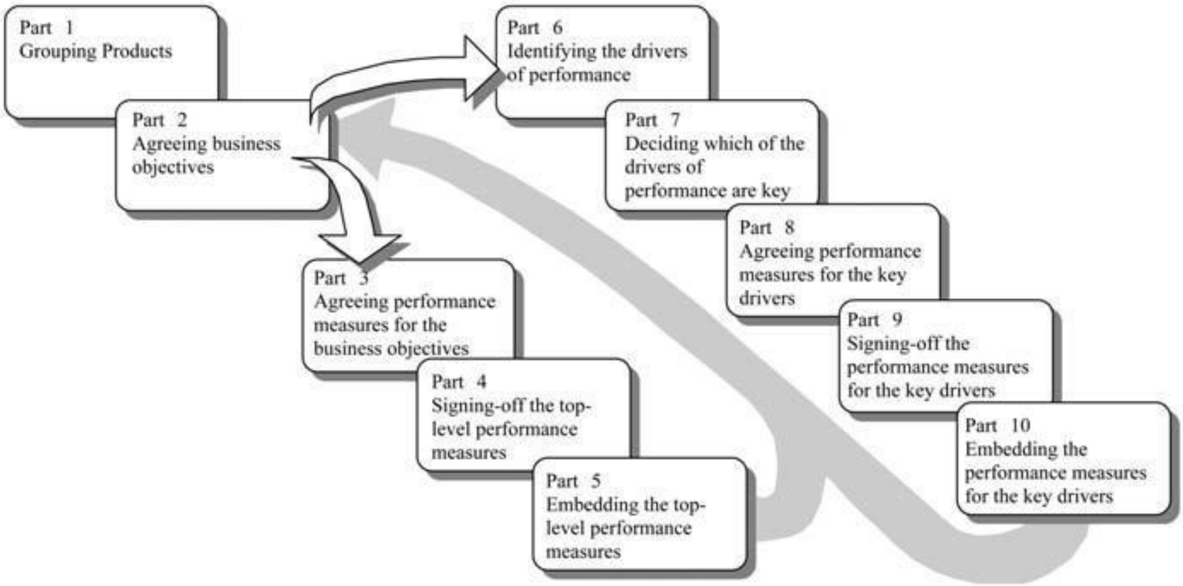


Figure 11 The process of designing a PMS (Neely et al., 2000)

The two presented instances provide guidelines which inform and shape the design process of PMSs. Both offer general steps towards the development of a PMS rather than being concerned with an individual research discipline. This enables organisations and researchers to adapt these models based on their own domain and interest. In contrast, some authors attempt to be more focused on a particular discipline. This is exemplified in the work of Medori and Steeple (2000) who introduced a six stage plan for PMS design process in manufacturing organisations as exhibited in Figure 12.

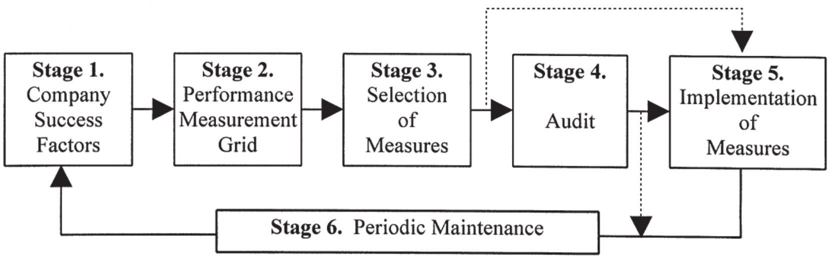


Figure 12 Integrated performance measurement framework outline (Medori & Steeple, 2000)

Another discipline-focused approach is reported in the work of Becker et al. (2009), where the authors compared previous maturity models collectively rather than investigating each of them separately. They compared and analysed 51 existing maturity models but found that only eight provide extensive information on their design process. This comparison offers a detailed review of critical elements when designing a PMS, and has led the authors to identify their procedure model.

In the reviewed literature, there are several approaches to help design a well-founded PMS. These approaches provide frameworks with research background, but in many cases they rarely offer companies with suggestions on how to choose their measure (Tangen, 2004). This is perhaps one of the most fundamental points which might, amongst other reasons, lead to the failure of PMSs. In Chapter 3, it will be explained how there is a lack of comprehensive study in regard to offering steps to designing AMs in the BIM domain.

2.8 PMSs barriers

There are many barriers facing the development and the applications of PMSs in different businesses. A five year action research project found that there are four main barriers to implementing PMSs (Nudurupati et al., 2011). These barriers are the time and effort required to carry out the assessment and analyse the result in busy businesses, the difficulty of applying the measures, the resistance to performance measurement and the 'new parent company initiatives'. Such reasons might have discouraged many businesses from developing and implementing PMSs and maintaining them.

Similarly, in the building environmental domain , Partidário (1996) identified the ten most common barriers to the implementation of environmental AMs. This includes the lack of experience and knowledge on deciding which variables to measure, shortage of resources including expertise and information, and the lack of available guidelines to apply the assessments. However, even those who apply PMSs in practice might fear the 'failure' of measurement initiatives which are caused by two main reasons: the poor design and the difficulty of implementation (Neely & Bourne, 2000).

Organisations have to identify the reasons of PMSs failure. They have, consequently, to update the PMSs and replace the old measures with new ones that suit the changing demands of businesses. Otherwise, a waste of time and money will be incurred by collecting data which no one is using (Neely et al., 2002).

2.9 Conclusion

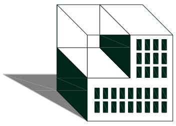
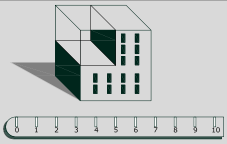
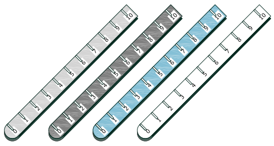
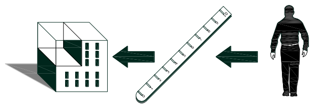
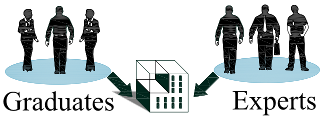
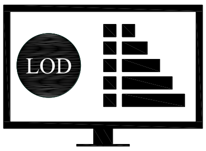
In the last century, a high level of academic, industrial and governmental interest has been directed to PMSs in different disciplines; stretching from budgetary control and business management to software engineering and environmental buildings. Indeed, the field of PMSs is taking central position in research, international policy-making process and political agendas and is shaping the effectiveness and efficiencies of a wide-range of businesses. PMSs have shifted from being solely evaluation systems towards new roles. They are also frameworks that link priorities, aims and goals with strategies and processes. They have, therefore, been used as communication tools and as methods to encourage dialogue, since assessments help managers focus their priorities and create a shared vision.

What makes a useful PMS is still one of the most critical and controversial questions in the field of performance measurement. This chapter has highlighted some perspectives on this by explaining the desirable characterisations of PMSs, and the varied design process approaches. If done well, PMSs will help moving companies forward. However, if poorly done, PMSs can result in creating misleading directions. By bringing together a range of different perspectives of PMSs, it is hoped to develop a research agenda of BIM-AMs that can engage with AMs in different research disciplines.

The field of PMSs is currently rising up in the BIM research agenda. A major reassessment of PMSs reviewed in Chapter 2 have informed and influenced the research field of BIM-AMs. This will be discussed in detail in Chapter 3.

3 Literature review: Current BIM-AMs:

Having discussed the wide-range of PMSs in different research disciplines in Chapter 2, this chapter provides a particular review of the literature in regard to BIM Assessment Methods (BIM-AMs). Their definitions, the evolution of the field, research approaches and examples of BIM-AMs will be discussed prior to identifying the applied research methods in Chapter 4.

1: Introduction	2: PMSs	3: BIM-AMs
		
Main questions included: What is BIM? What is the need for BIM-AMs?	Includes: - Brief history of the broad PMSs, their definitions - PMSs roles and barriers - Sample of PMSs	- Explains the wide range of BIM-AMs, their evolution, opportunities and challenges - Investigates how BIM-AMs have been informed by the broader PMSs
4: Research methodology	**5: Perspectives on BIM-AMs**	**6: Pilot Testing**
		
Introducing the chosen research methods including questionnaire, interview and the implementation of multiple AMs in practice	- Critical analysis of the BIM-AM, their similarities and differences - This includes the design process, the complexity and the range of measures	Initial testing of individual and multiple AMs in practice in association with a number of practices
7: Comprehensive testing	**8: Automated BIM-AM**	**9: Conclusions**
		
In association with Arup, applying three AMs to the same project and completed by six participants who have different BIM experience i.e. experts and graduates	Includes: - The need for automated AMs - The implementations of BIM-AM in practice	Current perspectives and future directions of BIM-AMs

3.1 Definitions of BIM-AMs

Clear definitions underpinning the phenomenon of BIM-AMs are a crucial starting point for understanding the research field of BIM performance measurement. The terms ‘scorecard’, ‘evaluation system’ and ‘maturity model’ are generally used in the literature of BIM performance measurement. In this thesis, they are coined as BIM-AMs. The first definition of BIM-AMs was provided by the National Institute of Building Science who defined BIM-AM as a tool to benchmark processes and practices in BIM projects (NIBS, 2007). Since then, most contributors have widely built on this definition with different aims, focus and perspectives. Some of the most recognisable definitions from the literature are:

- NBIMS-CMM (NIBS, 2007): A Capability Maturity Model (CMM) has been designed to help users assessing their business practices and processes in BIM **projects** “along a continuum or spectrum of desired technical level functionality”. The aim of the assessment is to enable stakeholders to track their current BIM levels of implementation, while looking to more goals for future directions.
- BIM Quickscan (Sebastian & Berlo, 2010): A tool that evaluates the BIM performance in an **organisation**. It contains an online questionnaire with 50 questions covering four main categories: organisations and management, culture, information structure and information flow; tools and applications.
- CPIx BIM Assessment Form (CPI, 2011): A method that evaluates the BIM competence and maturity of a project **member**. It consists of four sections: gateway questions, 12 areas of BIM, BIM Project Experience and BIM Capability questionnaire
- Organisational BIM Assessment Profile (CIC, 2013): A matrix designed to evaluate the **organisation’s** maturity both internally, to identify current status, and externally to analyse their performance within business market.
- Virtual Design and Construction (VDC) Scorecard (Kam et al., 2013b): A methodology that employs a comprehensive series of measures to track and assess the maturity of VDC applications and processes in **projects** across four main areas; planning, adoption, technology and performance.
- BIM-MM (Arup, 2014): A discipline-agnostic tool that assesses the maturity and success of BIM implementation within **projects**. It seeks to identify a common view of what is BIM best practice by enabling comparisons across projects within a company and also across the wider industry.

The definitions of BIM-AMs have been continually discussed in the current literature. Similar to PMSs, these definitions reflect one or a combination of two elements, namely, the characterisation of the assessment and its roles. These two elements, however, are influenced by the assessment's focus i.e. whether the AM evaluates BIM on the level of a project, an organisation, an individual or a team. Unlike the wider literature of performance measurement (Bourne et al., 2007; Moullin, 2007), there are no current publications in the BIM domain in which focus particularly on the definitions of AMs.

3.2 The evolution of BIM-AMs

The development of BIM-AMs is rooted in Software Engineering Institute's (SEI) CMM, initially developed in 1993, discussed in Section (Paulk, 1993). The CMM is a series of best practices which assist organisations to optimise their processes in order to provide better quality services to end-users and customers (Team, 2010). In 2007, the concept of CMM was picked up in the 'NBIMS, Version 1- Part 1: Overview, Principles and Methodologies' report, which introduced the NBIMS-CMM (NIBS, 2007). Developed in the U.S. by the NIBS, the standard has been widely recognised and cited by most researchers working in the field of BIM performance measurement.

Over the past decade, the NBIMS-CMM has evolved and its developers have released two updated versions in 2012 and 2015, all versions, however, include the same assessment content (NIBS, 2007, 2012, 2015). The NBIMS-CMM evaluates projects across eleven substantial BIM measures, such as Data Richness, Delivery Method, Business process and Graphical Information; themes that focus in particular on the information management area of BIM. It has been therefore criticised for not reflecting the diverse areas of BIM (Kam et al., 2013b). Others argued that the tool is incapable of assessing organisations, teams or individuals (Succar, 2010a).

So profound and powerful were these critics that the development of new models appeared, which tried to build on NBIMS-CMM and provide a wider application and more optimised models. These models attempted to combine information management measures with new evaluation criteria. Some tried to address broader concepts of BIM including education, resources, mentality and culture (Berlo et al., 2012). Others addressed further perspectives such as administration and managerial competencies (Change Agents AEC, 2013). In addition, new models suggested new evaluation focus i.e. organisations, teams and individuals.

This development peaked in 2009 with four new AMs offering more comprehensive measures and more integrated frameworks. These models are the *BIM Excellence Individual Assessments* (Change Agents AEC, 2013), the *BIM Maturity Matrix* (Succar, 2010a), the *BIM Proficiency Matrix* (Indiana University Architect's Office, 2009a) and the *BIM Quick Scan* (Sebastian & Berlo, 2010). No AMs were released in 2008 and 2010. Following these models, recent AMs have adopted even broader approaches and provided more detailed frameworks as with the Characterisation Framework (Gao, 2011) and the VDC Scorecard (Kam, 2015) which evaluate 74 and 56 measures respectively. Whilst these attempts reflect a broader vision of AMs, they have equally brought new challenges i.e. subjectivity and lack of case study projects, discussed in Section 3.5. Researchers, therefore, considered adding quantitative measures and offered more case studies in practice. AMs are flourishing within the ongoing dialogue of BIM literature with at least 16 AMs developed to date, the most recent being the BIM Level 2 BRE certifications, developed in the UK to certify businesses and practitioners (BRE, 2015a).

The evolution of this research field and its origins according to AMs' chronological order is presented in Table 6. Researchers in many countries worldwide are currently developing or have already developed tools and methodologies to evaluate BIM. Most of the existing AMs, however, have been developed in the U.S. (7AMs), followed by the UK (3AMs) and Australia (3AMs). A few AMs have been developed in the Netherlands, such as the BIM Meetlat (BIM measure indicator), they have been excluded in this study as they are not available in English. The only included Netherlands-based AM is the BIM Quick Scan which has been introduced in two publications in English (Berlo et al., 2012; Sebastian & Berlo, 2010).

These varied models evaluate not only projects, but also organisations, teams and individuals. They have also proposed novel approaches in evaluating BIM, and suggested more overarching frameworks that address the wider spectrum of BIM. They have individually and collectively contributed to the research field of BIM performance measurement. This contribution, however, varies to a great extent, since each AM has different degrees of strengths and weaknesses and different roles and emphasis (Azzouz, Shepherd, et al., 2016). Some assessments, for instance, are practical and user-friendly (Arup, 2014), available freely on-line (CIC, 2013), offer guidelines for usage (NIBS, 2007), and provide case study projects (Kam et al., 2013a). Other AMs are less practical, lack instructions or require an external assessor and fees to complete the assessment (BRE, 2015a), and suffer from the absence of case studies that explains the application of the AM in the AEC industry (VICO, 2011). All these themes will be analysed more comprehensively in Chapter 5.

Table 6 the origins of current BIM-AMs in chronological order

No	BIM-AM	Origin	Main Reference
1	NBIMS-CMM	U.S.	(NIBS, 2007)
2	BIM Excellence	Australia	(Change Agents AEC, 2013)
3	BIM Proficiency Matrix	U.S.	(Indiana University Architect's Office, 2009a)
4	BIM Maturity Matrix	Australia	(Succar, 2010a)
5	BIM Quick Scan	The Netherlands	(Sebastian & Berlo, 2010)
6	VICO BIM Score	Global company	(VICO, 2011)
7	Characterisation Framework	U.S.	(Gao, 2011)
8	CPIx BIM Assessment Form	UK	(CPI, 2011)
9	Organisational BIM Assessment Profile	U.S.	(CIC, 2013)
10	VDC Scorecard	U.S.	(Kam, 2015; Kam et al., 2013a, 2013b)
11	bimSCORE	U.S.	(bimSCORE, 2013) (Kam, 2015)
12	The Owner's BIMCAT	U.S.	(Giel, 2013)
13	BIM Maturity Measure	UK	(Arup, 2014)
14	Goal-driven method for evaluation of BIM project	South Korea	(Lee & Won, 2014)
15	The TOPC evaluation criteria	Australia	(Nepal et al., 2014)
16	BIM Level 2 BRE Certification	UK	(BRE, 2015a)

One of the leading authors of BIM research in general and on BIM-AMs in particular, is Bilal Succar, who has contributed considerably to this field over the last decade. Two key instances of his publications are the “BIM Maturity Matrix” (Succar, 2010a) and “Measuring BIM Performance: Five Metrics” (Succar et al., 2012). His work has been recognised by vast numbers of researchers and some of his papers have been amongst the most cited and downloaded articles. Other remarkable contributors are Kam (2015) and Giel (2013), with several publications in this field whilst building on previous PMSs in BIM and non-BIM domains. These scholars have engendered the research field of BIM-AMs, and they have been all contacted in the development process of this thesis to share ideas and exchange thoughts and experiences.

Analysis of the reviewed literature shows that there are four popular destinations for papers on AMs – two journals- the *Architectural Engineering and Design Management*, *Automation of Construction* – and two conferences- *the CIB World Congress* and the *Computing in Civil and Building Engineering*. In particular Automation in Construction has covered a wide-range of topics in regards to BIM performance measurement (Barlish & Sullivan, 2012; Succar & Kassem, 2015; Succar et al., 2013) and it has been the major destination for BIM articles in general (Elsevier, 2015). However, most AMs have been disseminated throughout their own institution. For instance, there are no journal or conference papers available on the 'BIM Proficiency Matrix', but the tool itself ,with introductory guidelines, is available on the website of Indiana University Architect's Office (2009b). Similar instances can be found with VICO BIM Score, CPIx BIM Assessment Form and BIM Level 2 BRE Certification.

3.2.1 Summary

Interest in BIM performance measurement has increased significantly in the last decade, with at least 16 AMs being developed. They have attracted the attention of policy-makers, researchers and AEC professionals, but as a whole, the research field is still lagging behind other disciplines such as building environmental AMs (Kam et al., 2013b). Given the multi-faceted and uncertain nature of BIM (Ahmad et al., 2012; Race, 2012), it is indeed difficult to set one single best way forward and a clear approach to identify what to measure when measuring BIM. This is perhaps the most fundamental reason for the inconsistency across the multiple AMs. Consequently, each assessment provides a unique perspective on BIM performance (although some of them borrow elements of previous models). In some circumstances, the AM is focused on an integrated approach that measures processes, information, strategies, infrastructure, use and personnel, as in the Organisational BIM Assessment, Figure 13 (CIC, 2013). In other circumstances, the framework is built on areas of planning, adoption, technology and performance as in the VDC Scorecard (Kam et al., 2013a), Figure 14. Both instances suggest main areas of measurement that relate directly to BIM that are influenced by the developers' aim and objectives. The challenge for AEC professionals is to decide which AM to use and which measures to prioritise, similar to the critical observations found of PMSs in Chapter 2.

Having discussed the evolution of BIM-AMs in the last decade, the following section will explore current research on AMs. In particular, the studies of this research field will be classified into five categories.

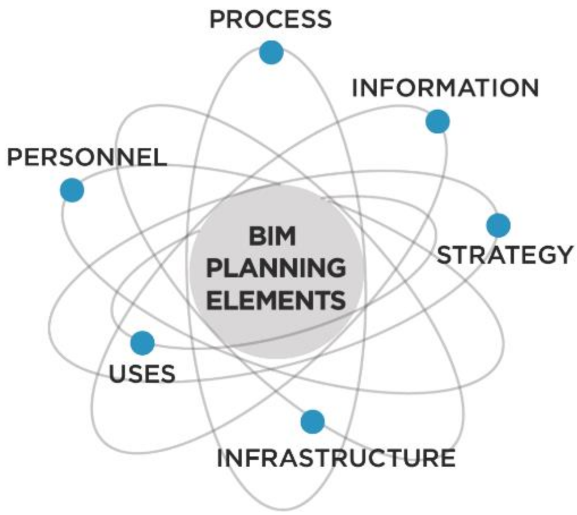


Figure 13 The BIM planning elements (CIC, 2013)

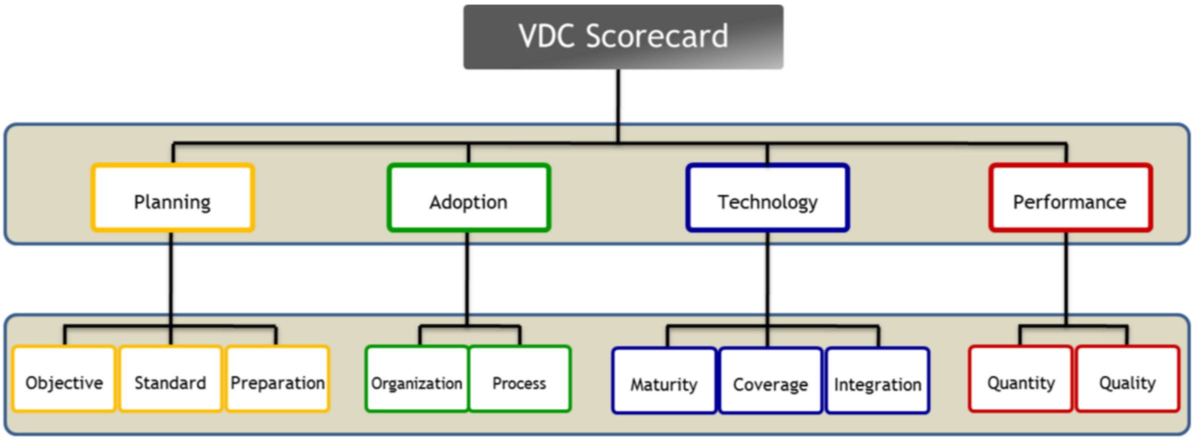


Figure 14 Main areas of measurement in the VDC Scorecard (Kam et al., 2013a)

3.3 Research approaches on BIM-AMs

The number of publications on BIM-AMs has grown steadily over the last decade. This growth was the highest in 2013 when nine reports, journals and conference papers were published including the work of CIC (2013), Giel and Issa (2013) and Kam (2013). Since then there has been a decrease in contributions with a total of eight publications between 2014 and 2015. These studies investigate a wide range of topics and can be classified in five major categories. Schweber (2013) suggests three types of research in the literature of AMs, namely, introduction of new AMs, comparison of past AMs and critique of existing AMs. Observations of the current publications on AMs suggests two additional categories; the design process of AMs and their implementation in practice. These two themes have been explicitly researched in the wider literature of performance measurement but partially addressed in the BIM agenda. Consequently, current studies of BIM-AMs cover one or a combination of the following categories (Figure 15), each will be explained in turn.

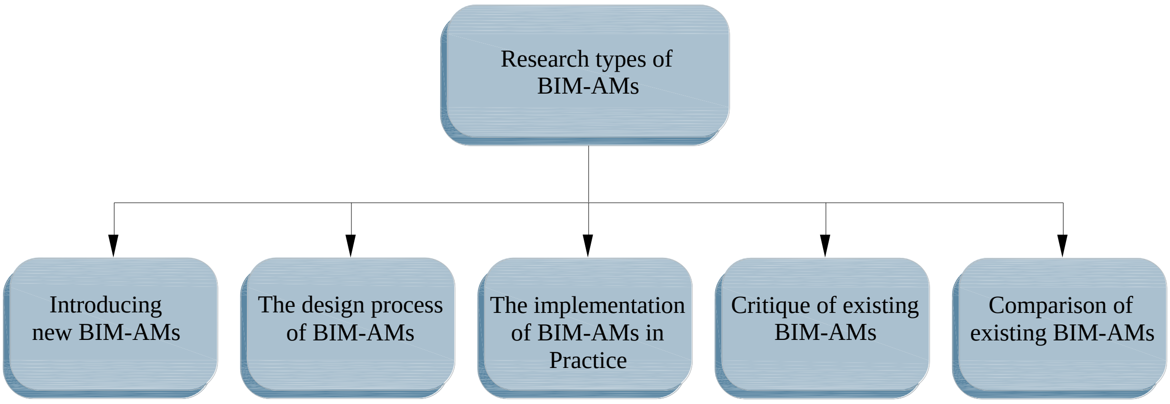


Figure 15 Research types of BIM-AMs

3.3.1 Introducing new BIM-AMs

Most current publications on BIM performance measurement (with over thirty sources) introduce and promote new AMs, for example (Arup, 2014; BRE, 2015b; Nepal et al., 2014). These publications vary in depth, scope and sophistication when introducing new emerging models. In some instances, past studies offer a comprehensive explanation of theoretical and technical background of these assessments. However, other studies suffer from the lack of documentation, whilst some of the methods are developed but no further research is carried out. The 'CPIx BIM Assessment Form', one of the three AMs developed in the UK, is available on-line, but it lacks publications describing the concept of the tool and the certifying process (CPI, 2011). Similarly, 'BIM Proficiency Matrix', developed a number of years earlier, was not supported by further documentation on its conceptual and methodological background (Indiana University Architect's Office, 2009a).

3.3.2 The design process of BIM-AMs

Existing BIM-AMs are valuable as they suggest frameworks which contain pre-selected measures in regard to BIM evaluation. However, they offer little guidance on how these measures have been selected, and how these frameworks have been shaped and designed. To be of practical value, these models have to justify the reason behind choosing these measures. Indeed, only a few studies explicitly explain the design process of their models, such as Gao (2011) and Giel (2013). However, there is no current study which focuses particularly on the design process of BIM-AMs, unlike many other disciplines which direct particular emphasis towards PMS design explained in Section 2.7 (De Bruin et al., 2005; Neely et al., 2005; Neely et al., 2000). A sample of the research methods applied to develop current BIM-AMs will be investigated in Section 5.8.

3.3.3 Implementation of BIM-AMs in practice

Relatively little research has been published on the implementation of BIM-AMs in practice despite the increasing development in BIM measurement research field. The shortage of case study projects is one of the main challenges in performance measurement since they offer little knowledge on the opportunities and challenges of AMs and since they shed light on how BIM is being used in the AEC businesses. Past researchers in the field of BIM-AMs tend to focus on presenting their own new models without, in many cases, applying them in practice. This lack of implementation makes it difficult for both academia and industry to explore the practicality of these AMs, their advantages and shortcomings. Section 5.7 will show how only seven of the current sixteen AMs are being supplemented with studies that focus on the implementation of these models in practice.

3.3.4 Critique of existing BIM-AMs

Critique of current AMs focuses on their opportunities and challenges. Contributors to this category tend to study particular or multiple past AMs in order to evaluate their formal features, advantages and disadvantages (Haron, 2013; Succar, 2010a). These studies can be described as assessments of assessment methods and can be found in at least thirteen publications (Chen, 2015; Chen et al., 2012; Giel & Issa, 2014; Giel & Issa, 2015; Giel, 2013; Haron, 2013; Jupp, 2013; Kam et al., 2013b; Lee & Won, 2014; NIBS, 2015; Sebastian & Berlo, 2010; Succar, 2010a, 2013). The majority of authors review past AMs to identify their limitations and address them when developing their own models. The 'points of departure' for Kam et al. (2013b) to design VDC Scorecard was to build upon the contributions of previous AMs. To do so, they explored the strengths and weaknesses of some eight assessments in the development process of their scorecard. Similarly, Sebastian and Berlo (2010) critically reviewed three past AMs when creating the BIM Quick Scan.

3.3.5 Comparison of existing BIM-AMs

Despite the growing research on BIM-AMs, most previous studies tend to focus on introducing individual models rather than comparing all of them as a whole. Exceptions can be found only in a handful of previous studies which emphasise the similar and different characterisations of existing AMs, such as the evaluation style, range of measures and intended user groups. In Table 7, five resources on BIM-AMs' comparison are listed. In addition, the number of compared AMs (a maximum of seven AMs) and the addressed characteristics of comparison are presented.

Table 7 Current research on BIM-AMs comparison

Reference	No of compared AMs	Compared characterisations
(Giel, 2013)	6	• Rating context • Evaluation style • Measurement categories and weightings • Number of maturity levels • Evaluation context
(Giel & Issa, 2014)	4	• Intended user group • Rating context • Evaluation style • Measurement categories and weightings • Number of maturity levels
(Giel & Issa, 2013)	6	• Evaluation context
(NIBS, 2015)	7	• Same as in (Giel, 2013)
(Dakhil, 2015)	6	• The beneficiary • Number of maturity levels • Key elements and category • Evaluation method

As seen in the table above, main contributors to this field are Brittany Giel and co-authors. Giel, carried out a comprehensive comparison of BIM-AMs for her PhD research and explored some of their key features (Giel, 2013), with particular focus on evaluation context and the measures included in each AM (Giel & Issa, 2013). In 2015, the NIBS, who developed the first BIM-AM (NBIMS-CMM) in 2007, updated their standard and included a brief snapshot of seven AMs, based on Giel's work. According to NIBS, this comparison is needed to illustrate the wealth of resources on measuring BIM. Professionals, therefore, could choose the 'best tool' for adoption according their desired goals and visions (NIBS, 2015). Such studies with comparative approach of existing AMs reflect the extensive body of knowledge of BIM-AMs and engender assessments' research agenda. A sample of Giel's work is presented in Table 8 which shows a comparison of six AMs against four distinguishing properties.

Table 8: Comparison of six BIM-AMs. Source (Giel, 2013)

Parameter	NBIMS ICMM	BIM Maturity Matrix	BIM Proficiency Matrix	BIM QuickScan	VDC Scorecard/BimScore	Owner Maturity Matrix
Rating context	Projects	Organisations, teams, individuals	Contractor's and designer's ability to apply BIM	Organisations	Projects	Owner's BIM maturity of planning strategies
Evaluation style	Self-evaluation with external reviewer for validation	Four forms of evaluation according to granularity level	Self-evaluation	External licensed assessor or self-scan when using the web AM	Self-evaluation using the Excel template or web based dashboard	Self-evaluation
Measures and weightings	Eleven measures weighted on importance	Twelve measures equally weighted	Eight measures equally weighted	Four chapters with fifty questions 'based on weighted KPI'	Four areas and ten sub-areas weighted on importance	Sixteen measures equally weighted
Number of maturity levels	10	5	4	None	5	6

The research approach of comparison is different from the previous category .i.e. Critique of current AMs. Researchers of comparative studies provide cross case synthesis of assessments to capture the whole picture of the research field and compare and contrast similarities and differences, whilst those who focus on critic of AMs explore the challenges and limitation of an individual or a sample of AMs without necessarily providing a collective approach to understand the research field as coherent whole.

3.4 Benefits and roles of BIM-AMs

With the uncertainty surrounding the definition of BIM, lack of guidance on implementing it, and the enormous challenges in measuring its benefits (Barlish & Sullivan, 2012), it is vital for professionals to adopt BIM-AMs to track their progress, focus their strategy and translate data into knowledge and create a common view of BIM best practice. According to past researchers, AMs offer several roles and have many advantages as they have the ability to:

- Help companies on two levels; internally to identify their current status and externally to compare with other businesses in the AEC industry (CIC, 2013).
- Enable organisations and teams to benchmark their own BIM competencies and assess their own successes and (or) failures (Succar et al., 2012).
- Develop a roadmap for stakeholders to assist them identifying goals for their future plans (NIBS, 2007).
- Help academia and industry to distinguish a 'healthy feedback loop' of BIM capacity in practice. This feedback may assist professionals to improve their BIM adoption and increase their investments' returns (Kam et al., 2013b).
- Provide the industry with an overall picture of the BIM implementation maturity within the overall life-cycle of a building (McCuen et al., 2012).
- Help firms to objectively manage their BIM investments in projects, decrease uncertainty and direct financial and human resources into particular tasks (Kam, 2015).
- Organise project data into categories and measures to consistently evaluate projects. This evaluation might help researchers and managers to compare projects across the evaluated measures (Gao, 2011).
- Offer a country-to-country comparison when applied on an international level (Kam, 2013; Kassem et al., 2013).

Since innovation is diffusing across the AEC industry and since the AEC businesses are becoming highly competitive, the need for AMs is becoming paramount (Månsson & Lindahl, 2016; Taticchi et al., 2010). BIM-AMs offer opportunities for improvement by identifying areas of strengths and weaknesses. At the decision makers' level, the results of BIM-AMs provide governments and local authorities with a better understanding of the current position of BIM implementation. At the company level, professionals can use the results to compare capabilities between different projects and teams internally. They can also help companies to optimise their staff performance and influence individuals to improve their implementation of BIM (including training and education).

3.5 Barriers and challenges of BIM-AMs

Despite these advantages and roles, most BIM-AMs have not been widely acknowledged and adopted in the AEC industry (Sebastian & Berlo, 2010). The majority of scholars suggest that the main barrier to adoption is linked to the challenges facing current BIM-AMs. Following their review of seven assessments, Kam et al. (2013b) highlight many deficiencies of past assessments. Some of the deficiencies of AMs include:

- Incomplete evaluation systems.
- Shortage of tangible benefits to encourage AEC professionals to apply AMs.
- Unsupported decision making process.
- Lack of clarity surrounding the frameworks and their definitions which make it difficult for professionals to implement.
- Lack of guidelines or instructions for use.
- Little support from contributors and sponsors.
- Shortage of case study projects which is crucial for validation.
- The absence of a unified AM which evaluates both projects and organisations at the same time (Jupp, 2013; Sebastian & Berlo, 2010).
- Challenges in selecting the appropriate measures, and the difficulties in evaluating the quantitative benefits of BIM (Lee & Won, 2014). The Organisational BIM Assessment Profile, for instance, provides little detail on how the assessment measures are chosen and weighted (Giel & Issa, 2014).
- Struggle to achieve objective measures with difficulties in providing scientific analysis to validate the results of the AMs (Sebastian & Berlo, 2010).

- The lack of metric-based and objective measures. Most BIM-AMs lack a systematic and objective approach of evaluating BIM level of maturity (Kam, 2013, 2015). Since some of the measures, as in NBIMS-CMM, are subjective and open to interpretation, it is possible that two participants completing the same assessment on the same project would disagree on the levels of maturity of each measure (NIBS, 2007), this has been tested and discussed in Chapters 6 and 7.
- Most current BIM-AMs received little widespread in academia and the AEC industry since they are based on lengthy interviews and surveys with professionals (Lee & Won, 2014). For instance, when applying the VDC Scorecard Express version on 108 pilot projects, the average interviewing time taken for the assessment was four hours (Kam et al., 2013a).
- Some of the tools have been criticised for focusing on technology and obscuring other areas of interest such as processes and policies of BIM (Chen et al., 2012).

Furthermore, some of the new AMs have been criticised for limiting interest since they require fees access (Chen, 2015). bimSCORE (2013) is an AM that provides a brief free assessment online (FREE 004 version). However, it requires a fee to access its 'NOW 010' version, which provides written and concise results on BIM maturity. Similarly, the most recent BIM Level 2 BRE certifications require an external examiner to carry out the assessment and costs between £2000 and £5000 depending on the company's size (BRE, 2015a).

The implementation of BIM-AMs brings with it a wide range of practical, methodological and cultural challenges. In regards to practical challenges, the literature of early BIM-AMs was criticised for being narrowed down to focus either on the software industry or the procedural sides of the BIM implementation process (Succar, 2010a). However, since the field of AMs has gradually proliferated, more recent models and tools have shifted to assess wider measures (Chen et al., 2012). In terms of methodology, the principal challenge of current AMs is their dependency on qualitative methods of measurement. In order to improve this research field, professionals and researchers should address current challenges, in particular, subjectivity. As Kam (2015) notes when highlighting the need for organisations and policies to turn aspirations into quantitative measures:

> "If the building industry is to unlock the potential of BIM, it must apply objective, repeatable and reliable metrics and learn how to extend successful approaches across project portfolios. The methodologies must include reliable evaluation and quantitative

measures of performance to help organisations optimise the business decision making, processes and technologies that are used to support the cycle of the built environment."

3.6 Examples of BIM-AMs

Having discussed the evolution of BIM-AMs, their categorisation, their intentions and roles, this section will present three BIM-AMs in detail. The three AMs are the BIM Maturity Matrix, the Organisations BIM Assessment Profile and the Characterisation Framework; all research based AMs.

3.6.1 BIM Maturity Matrix

The BIM Maturity Matrix, first introduced in 2009 by Bilal Succar, is a knowledge tool that assesses BIM performance milestones. Since its development, the BIM Maturity Matrix has proved to be popular as it is acknowledged and cited in most studies on BIM measurement. The assessment covers three major BIM competency areas, namely, technology, process and policy (Succar, 2010a) rather than being limited to one aspect of BIM. Each of these areas, however, is broken down into subareas with a total of ten sub-areas. The three areas and their sub-areas are all presented in Table 9.

Table 9 BIM competency areas and subareas of 'BIM Maturity Matrix'(Succar, 2010a)

BIM competency areas	Sub-areas	Refers to:
Technology	Software	Applications deliverables and data
	Hardware	Equipment, deliverables and location/mobility
	Network	Solutions, deliverables and security/access control
Process	Infrastructure	Physical and knowledge related
	Products and services	Specification, differentiation, project delivery approach and R&D
	Human resources	Competencies, roles, experience and dynamics
	leadership	Innovation and renewal, strategic, organisational, communicative and managerial attributes
Policy	Regulatory	Rules/directives, standards/classifications, guidelines/benchmarks and codes/regulations
	Contractual	Responsibilities, rewards and risks
	Preparatory	Research

The matrix consists of five levels of maturity which reflect the possible evolutionary steps of each sub-area. These levels are: ‘a Initial’, ‘b Defined’, ‘c Managed’, ‘d Integrated’ and ‘e Optimised’ (Figure 16).

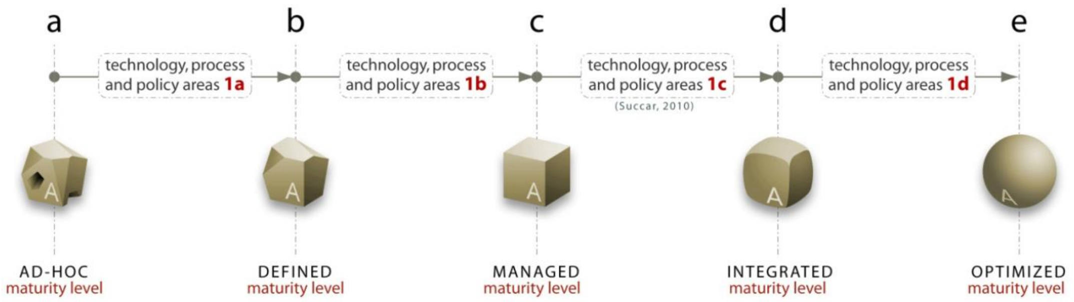


Figure 16 BIM maturity levels (Succar, 2010b)

Table 10 presents a sample of the assessment, in particular it shows the first third of the assessment which covers ‘Technology’ with its three sub-areas. It also illustrates how each sub-area is assigned to five maturity levels. Based on the selected maturity levels, an average maturity score can be obtained.

BIM Maturity Matrix is one of the ‘most ambitious’ BIM-AMs (Månsson & Lindahl, 2016), perhaps because it overcomes the shortcomings of previous AMs, in particular the NBIMS-CMM (Giel, 2013). Unlike the NBIMS-CMM, which focuses mainly on information management, the BIM Maturity Matrix introduces an integrated framework that focuses on wider aspects of BIM. This is similar to the approach undertaken in the Balanced Scorecard which combined different performance measures rather than focusing only on traditional ones.

Some authors have attempted to develop frameworks based on the BIM Maturity Matrix. Such attempts tend to use the BIM Maturity Matrix to identify the key measures and categories. Researchers at the University of Salford have developed a conceptual framework to help clients understand the benefits of BIM through the project life cycle (Dakhil & Alshawi, 2014). They compared three previous maturity models, including Succar’s matrix, as a methodological approach to select the desired components of their framework. In another study, the BIM Maturity Matrix combined with the NBIMS-CMM were used to create a BIM Maturity framework. The model includes 27 measures, 16 of them are taken from the BIM Maturity Matrix and 11 from the NBIMS-CMM. These two instances show how Succar’s work has informed and shaped the emergence of new frameworks. One of its main limitations, however, is the lack of case study projects in the AEC industry.

Table 10 BIM Maturity Matrix, Technology part (Succar, 2010a)

	BIM Competency Areas at Granularity level 1	a INITIAL	b DEFINED	c MANAGED	d INTEGRATED	e OPTIMISED
TECHNOLOGY	**Software:** applications, deliverables and data	Usage of software applications is unmonitored and unregulated. 3D Models are relied on to mainly generate accurate 2D representations/deliverables. Data usage, storage and exchanges are not defined within organisations or project teams. Exchanges suffer from a severe lack of interoperability.	Software usage/introduction is unified within an organisation or project teams (multiple organisations). 3D Models are relied upon to generate 2D as well as 3D deliverables. Data usage, storage and exchange are well defined within organisations and project teams. Interoperable data exchanges are defined and prioritised.	Software selection and usage is controlled and managed according to defined deliverables. Models are the basis for 3D views, 2D representations, quantification, specification and analytical studies. Data usage, storage and exchanges are monitored and controlled. Data flow is documented and well-managed. Interoperable data exchanges are mandated and closely monitored.	Software selection and deployment follows strategic objectives, not just operational requirements. Modelling deliverables are well synchronised across projects and tightly integrated with business processes. Interoperable data usage, storage and exchange are regulated and performed as part of an overall organisational or project-team strategy.	Selection/use of software tools is continuously revisited to enhance productivity and align with strategic objectives. Modelling deliverables are cyclically being revised/ optimised to benefit from new software functionalities and available extensions. All matters related to interoperable data usage storage and exchange are documented, controlled, reflected upon and proactively enhanced.
	Hardware: equipment, deliverables and location/mobility	BIM equipment is inadequate; specifications are too low or inconsistent across the organisation. Equipment replacement or upgrades are treated as cost items and performed only when unavoidable.	Equipment specifications – suitable for the delivery of BIM products and services - are defined, budgeted-for and standardised across the organisation. Hardware replacements and upgrades are well-defined cost items.	A strategy is in place to transparently document, manage and maintain BIM equipment. Investment in hardware is well-targeted to enhance staff mobility (where needed) and extend BIM productivity.	Equipment deployments are treated as BIM enablers. Investment in equipment is tightly integrated with financial plans, business strategies and performance objectives.	Existing equipment and innovative solutions are continuously tested, upgraded and deployed. BIM hardware become part of organisation's or project team's competitive advantage.
	Network: solutions, deliverables and security/ access control	Network solutions are non-existent or ad-hoc. Individuals, organisations (single location/ dispersed) and project teams use whatever tools found to communicate and share data. Stakeholders lack the network infrastructure necessary to harvest, store and share knowledge.	Network solutions for sharing information and controlling access are identified within and between organisations. At project level, stakeholders identify their requirements for sharing data/information. Dispersed organisations and project teams are connected through relatively low-bandwidth connections.	Network solutions for harvesting, storing and sharing knowledge within and between organisations are well managed through common platforms (e.g. intranets or extranets). Content and asset management tools are deployed to regulate structured and unstructured data shared across high-bandwidth connections.	Network solutions enable multiple facets of the BIM process to be integrated through seamless real-time sharing of data, information and knowledge. Solutions include project-specific networks/portals which enable data-intensive interchange (interoperable exchange) between stakeholders.	Network solutions are continuously assessed and replaced by the latest tested innovations. Networks facilitate knowledge acquisition, storing and sharing between all stakeholders. Optimisation of integrated data , process and communication channels is relentless.

3.6.2 Organisational BIM Assessment Profile

In 2013, the Computer Integrated Construction Research Programme at Pennsylvania State University developed the Organisational BIM Assessment Profile to assess an organisation's maturity in regards to BIM (CIC, 2013). It aims to help organisations identify their current maturity and determine their BIM performance across the wider construction industry. The feedback collected from this assessment assisted in shaping future processes and technologies, which are needed to enable opportunities for improvement. The Organisational BIM Assessment Profile is a matrix that consists of six areas (i.e. strategy, BIM uses, process, information, infrastructure and personnel) and twenty 'planning elements' (Table 11).

Table 11 Organizational BIM Assessment Profile's content

Strategy	BIM Uses	Process	Information	Infrastructure	Personnel
Organizational Mission and Goals	Project Uses	Project Processes	Model Element Breakdown (MEB)	Software	Roles and Responsibilities
BIM Vision and Objectives	Operational Uses	Organizational Processes	Level of Development (LOD)	Hardware	Organizational Hierarchy
Management Support			Facility Data	Physical Spaces	Education
BIM Champion					Training
BIM Planning Committee					Change Readiness

To complete the assessment, participants have to determine the current maturity level of each element. This would be based on the brief description of maturity levels provided in the matrix (Table 12). These levels range from '0 Non-Existent' which means that the element is not used or existent within the organisation and continues to level '5 Optimizing' in which the planning element is most advanced. Once the organisation has completed the assessment, an overall score will be obtained. Based on the assessment's outcome, organisations can map their current status (highlighted in blue in Table 12). This in turn assists BIM managers to identify their desired level of BIM implementation for each particular measure (highlighted in red in Table 12). However, it is important to note that organisations might not need to advance each measure to level 5, this will depend on their aim and objectives.

Table 12 A snapshot of the Organisational BIM Assessment Profile (CIC, 2013)

Planning Element	Description	Level of Maturity						Current Level	Target Level	Total Possible
Strategy	the Mission, Vision, Goals, and Objectives, along with management support, BIM Champions, and BIM Planning Committee.	**0 Non-Existent**	**1 Initial**	**2 Managed**	**3 Defined**	**4 Quantitatively Managed**	**5 Optimizing**	**11**	**17**	**25**
Organizational Mission and Goals	A **mission** is the fundamental purpose for existence of an organization. **Goals** are specific aims which the organization wishes to accomplish.	No organizational mission or goals	Basic organizational mission established	Established basic organizational goals	Organization mission which addressed purpose, services, values (at a minimum)	Goals are specific, measurable, attainable, relevant, and timely	Mission and goals are regularly revisited, maintained and updated (as necessary)	**1**	**3**	**5**
BIM Vision and Objectives	A **vision** is a picture of what an organization is striving to become **Objectives** are specific tasks or steps that when accomplished move the organization toward their goals	No BIM vision or objectives defined	Basic BIM vision is establish	Established Basic BIM Objectives	BIM Vision address mission, strategy, and culture	BIM objectives are specific, measurable, attainable, relevant, and timely	Vision and objectives are regularly revisited, maintained and updated (as necessary)	**2**	**3**	**5**
Management Support	To what level does management support the BIM Planning Process	No management support	Limited support for feasibility study	Full Support for BIM Implementation with some resource commitment	Full support for BIM Implementation with appropriate resource commitment	Limited support for continuing efforts with a limited budget	Full support of continuing efforts	**3**	**4**	**5**
BIM Champion	A BIM Champion is a person who is technically skilled and motivated to guide an organization to improve their processes by pushing adoption, managing resistance to change and ensuring implementation of BIM	No BIM Champion	BIM Champion identified but limited time committed to BIM initiative	BIM Champion with adequate time commitment	Multiple BIM Champions with each working Group	Executive Level BIM Support Champion with limit time commitment	Executive-level BIM Champion working closely with working group champion	**3**	**4**	**5**
BIM Planning Committee	The BIM Planning Committee is responsible for developing the BIM strategy of the organization	No BIM Planning Committee established	Small Ad-hoc Committee with only those interested in BIM	BIM Committee is formalized but not inclusive of all operating units	Multi-disciplinary BIM Planning Committee established with members from all operative units	Planning Committee includes members for all level of the organization including executives	BIM Planning decisions are integrated with organizational Strategic Planning	**2**	**3**	**5**
BIM Uses	The specific methods of implementing BIM	**0 Non-Existent**	**1 Initial**	**2 Managed**	**3 Defined**	**4 Quantitatively Managed**	**5 Optimizing**	**2**	**5**	**10**
Project Uses	The specific methods of implementing BIM on projects	No BIM Uses for Projects identified	Minimal owner requirements for BIM	Minimal BIM Uses required	Extensive use of BIM with limited sharing between parties	Extensive use of BIM with sharing between parties within project phase	Open sharing of BIM data across all parties and project phases	**1**	**3**	**5**
Operational Uses	The specific methods of implementing BIM within the organization	No BIM Uses for Operations identified	Record (As-Built) BIM model received by operations	Record BIM data imported or referenced for operational uses	BIM data manually maintained for operational uses	BIM data is directly integrated with operational systems	BIM data maintained with operational systems in Real-time	**1**	**2**	**5**
Process	The means by which the BIM Uses are accomplished	**0 Non-Existent**	**1 Initial**	**2 Managed**	**3 Defined**	**4 Quantitatively Managed**	**5 Optimizing**	**2**	**5**	**10**
Project Processes	The documentation of External Project BIM Processes	No external project BIM processes documented	High-level BIM process documented for each party	Integrated high-level BIM process pocumented	Detailed BIM process documented for primary BIM Uses	Detailed BIM process documented for all BIM Uses	Detailed BIM process documented and regularly maintained and updated	**1**	**3**	**5**
Organizational Processes	The documentation of Internal Organizational BIM Processes	No internal organizational BIM processes documented	High-Level BIM process documented for each operating unit	Integrated high-level organizational process documented	Detailed BIM process documented for primary organizational Uses	Detailed BIM process documented for all BIM Uses	Detailed BIM Process documented and regularly maintained and updated	**1**	**2**	**5**

The Organisational BIM Assessment Profile is built on previous models. It addresses software and hardware when measuring infrastructure, both elements were earlier evaluated in Succar's work. It also measures the Level of Detail, which was previously suggested in NBIMS-CMM. However, the assessment has contributed significantly to the field of BIM-AMs and influenced later models. At the time of its development, it introduced a new means of measuring BIM and suggested new directions of evaluation. More recent AMs have been greatly influenced by this model in regard to their structure and content. For instance, the Arup's BIM Maturity Measure has a similar structure and uses the same levels of maturity. Arup's model also borrowed a couple of measures including the 'BIM Champion' and 'Level of Development' (Arup, 2014). However, some of the limitations of this model are the absence of explanations of its design process and how the measures have been prioritised and the lack of implementation in practice.

3.6.3 Characterisation Framework

Characterisation Framework was developed by Gao (2011) as part of her Ph.D. at the CIFE centre at Stanford University. The aim is to compare and document the implementation of BIM in construction projects in a structured, sufficient and consistent way. By evaluating BIM, the developer attempts to gain insights into BIM implementation and maximise its benefits. The framework organises project's data into a classification of three categories, fourteen factors and 74 measures. The main three main categories are Project Context, Implementing BIM on a Project, and Impacts on BIM Implementations, as presented in Table 13. The framework attempts to sufficiently and consistently answer eight critical questions:

1. Why to use BIM?
2. When to use BIM?
3. Who are the involved stakeholders?
4. What level of detail is required?
5. Which BIM software to use?
6. What is the BIM workflow?
7. How much cost and effort is needed?
8. What are the benefits of BIM implementations?

The areas covered in this framework draw on these eight questions. At the time of its development, the framework was the first to provide such a detailed and substantial approach of evaluating BIM in projects, reflected in an eight-page questionnaire. The framework provides detailed explanation of every measure and identifies the desired features of AMs.

Table 13 Main categories and factors addresses in the Characterisation Framework (Gao, 2011)

Categories	Factors
A **Context**	A1 Project Context
	A2 Company Context
B **Implementation**	B1 Model Uses
	B2 Timing of BIM
	B3 Stakeholder Involvement
	B4 Modeled Data: Modelled Scope
	Modelled Data: Model Structure
	Modelled Data: Level of Detail
	Modelled Data: Data Exchange
	B5 (B5a) Software Tools: Software Functionality
	(B5b) Software Tools: Software Interoperability
	B6 Workflow
	B7 Effort and Cost
C **Performance Impacts**	C1 Perceived Impacts on Product
	C2 Perceived Impacts on Organization
	C3 (C3a) Perceived Impacts on Process: Design Process
	(C3b) Perceived Impacts on Process: Construction Process
	(C3c) Perceived Impacts on Process: Operation and Maintenance Process
	C4 Quantifiable Progress Performance during Project Run-time
	C5 Quantifiable Final Performance upon Project Completion

However, despite this contribution to BIM measurement research field, Kam et al. (2013b) have criticised the Characterisation Framework for not providing a practical model. According to them, its ‘research oriented approach’ prevented the framework from offering a continuous, repeatable, active and accessible evaluation system. Despite that, observations of the VDC Scorecard (developed by Kam and co-authors), shows significant similarities with the Characterisation Framework in terms of depth, and structure, and with many measures in common such as the level of detail and data sharing method. Another critical limitation is linked to the design process of the framework and to its validation. Gao extracted the chosen measures from historic case study projects and has not been tested on new projects (Chen, 2015).

3.6.4 Summary

The three BIM-AMs presented reflect the richness and the maturation of the research agenda of BIM-AMs. Each offers a novel and different angle for measuring BIM performance. They have suggested new emerging areas of measurement, and unlike the first BIM-AM, the NBIMS-CMM, they addressed different aspects of BIM. The BIM Maturity Matrix was the first framework that focuses on integrated approaches i.e. the combination of policies, process and technologies. The Organisational BIM Assessment Profile proposes several new areas which have influenced more recent models, in particular Arup's Maturity Matrix. The Characterisations Framework was the first thorough and comprehensive AM of projects which seems to have some aspects of the later VDC Scorecard. There is no doubt, however, that later models have been built upon earlier ones and similarities can be found in some common critical measures.

3.7 The influence of PMSs on BIM-AMs

BIM-AMs initiatives have been noticeably influenced and rooted in PMSs in different disciplines. In the first released BIM-AM, the developers of NBIMS-CMM highlight that the idea is originated in the field of software engineering. This linkage helped the NBIMS's developers to structure their assessment and identify areas of opportunities and challenges (NIBS, 2007). In the following years, other BIM-AMs were influenced by non-BIM assessments. The work of Succar is rooted in non-BIM maturity models. In his early studies in 2010, Succar built his BIM Maturity Matrix on the widely adopted models in different disciplines, in particular quality management (Succar, 2010a). To do so, Succar investigated at least eighteen frameworks and CMMs (mainly from outside the AEC sector) to 'tailor' his knowledge tools and shape his later developments.

This extensive examination of multi-disciplinary models included their structure, conceptual depth, target audience and employed levels of maturity (Succar et al., 2012). Further evidence of the impact of PMSs on BIM-AMs is reported in the research carried out by Giel who investigated the history of maturity evaluation and provided a snapshot of eleven models from the construction domain, supply chain management and business process (Giel, 2013). This has also been reinforced by CIFE researchers (Kam et al., 2013a) who note:

> "The Virtual Design and Construction Scorecard was designed, building upon points of departure from other research institutions and industry partners in the building industry,

such as the Leadership in Energy and Environmental Design, and the Comprehensive Assessment System for Built Environment Efficiency, as well as evaluation frameworks and scoring systems adopted by other industries such as, Balanced Scorecard, Credit Score, The Michelin Guide and Wine Scoring."

The VDC Scorecard attempts to overcome previous shortcomings by adding more comprehensive and more multi-dimensional measures in a 'balanced' approach. It is clear that BIM-AMs have been shaped and influenced by the wide development of PMSs, in particular, the business performance measurement, environmental AMs and the software engineering CMMs. BIM-AMs, have also informed each other, but they originated in the broader field of PMSs in different disciplines. Observations of the evolution of PMSs and BIM-AMs discussed in Chapter 2 and Chapter 3 respectively show the strong link between the inter-disciplinary fields. Figure 17 shows a sample of different BIM-AMs and the external influences that shaped their development.

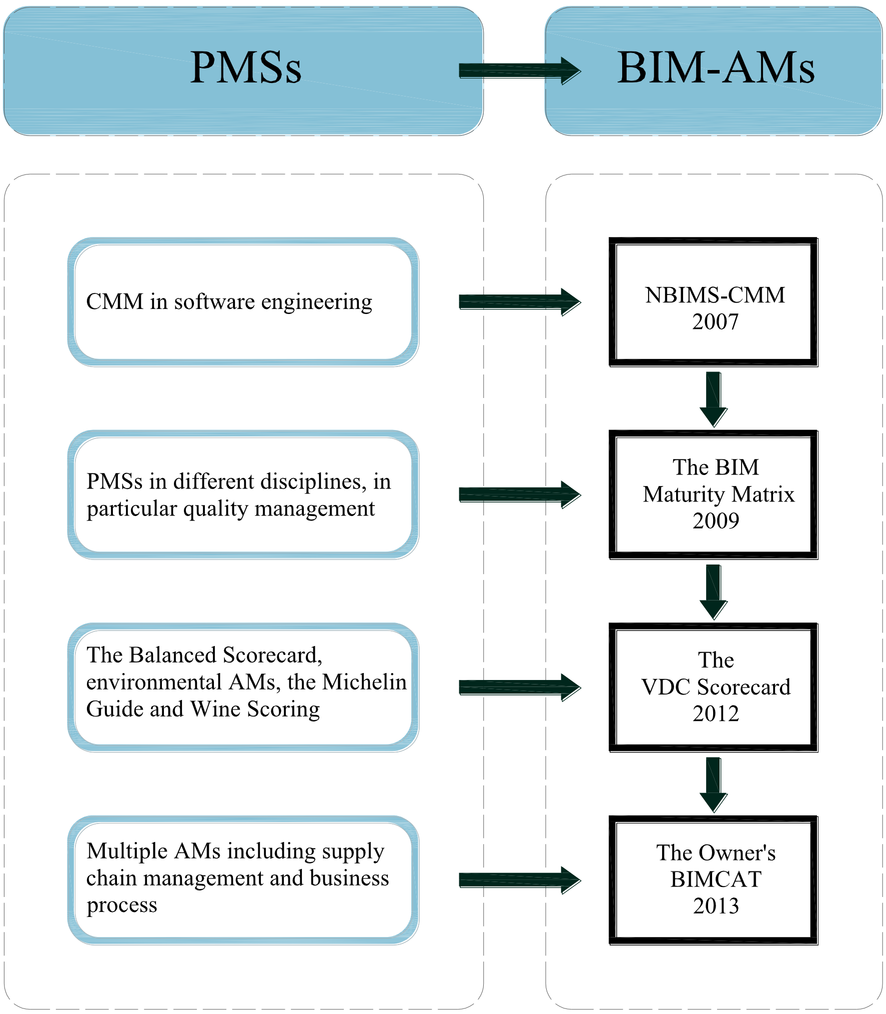


Figure 17 The impact of PMSs on BIM-AMs

3.8 Adjusted aim and objectives

Having reviewed the BIM-AMs literature, new themes and research questions have emerged. This study started with an initial aim to explore the evolution of BIM-AMs (introduced in Section 1.4). However, it was noted in the literature that the research field of BIM-AMs is still facing multiple challenges. Through previous studies, there is a tendency to introduce new AMs with a shortage of studies that comprehensively compare these AMs and apply the assessments in practice. In addition, most current AMs are heavily dependent on human judgement and include a high level of qualitative measures. It was therefore hypothesised that two participants completing the same AM might likely record significantly different scores, raising concerns about credibility and validity. It was also hypothesised that automation might play an important role in the future of BIM-AMs which is essential to create accurate and quick feedback on BIM implementation in practice. These hypotheses are predictions about the outcomes of this research and they will be observed throughout the rest of the thesis. Based on these hypotheses, the following chapters aim to identify perspectives which help AEC businesses to develop and implement BIM-AMs in practice. To address this aim, three main objectives are identified:

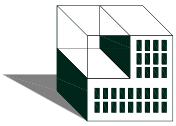
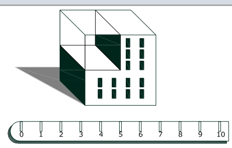
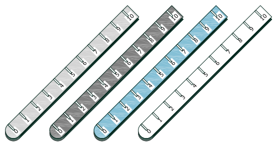
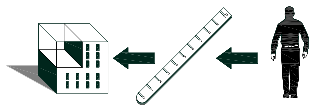
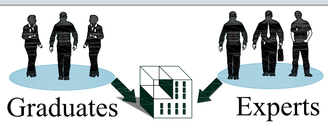
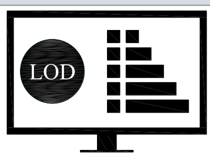
1. To better understand the relationship between current AMs, their similarities and differences.
2. To examine the consistency of a number of current AMs when applied in practice.
3. To develop an approach that automates an element of the BIM-AMs.

3.9 Conclusion

BIM performance measurement started in 2007 with the development of NBIMS-CMM, influenced by software engineering CMM. Since then, the literature of BIM measurement has gradually grown. Multiple conflicting BIM-AMs have emerged developed by academics and professionals. Each of the existing AMs has offered a unique perspective in regard to BIM performance (with overlap in some models). Most of the studies, however, focus on introducing new models with less research directed towards the design process of AMs and their implementation in practice.

4 Research design and methods

Having conducted the literature review on PMSs and BIM-AMs in Chapters 2 and 3, a discussion of the research design and the applied research methods is presented in this chapter. A mixed research method is selected to explore BIM-AMs from different angles, instead of relying on a single research method or approach. In addition, this chapter provides an explanation of the chosen methods which includes literature review, comparative method, multiple case study projects (interviews and testing of AMs) and a questionnaire.

1: Introduction	2: PMSs	3: BIM-AMs
		
Main questions included: What is BIM? What is the need for BIM-AMs?	Includes: - Brief history of the broad PMSs, their definitions - PMSs roles and barriers - Sample of PMSs	- Explains the wide range of BIM-AMs, their evolution, opportunities and challenges - Investigates how BIM-AMs have been informed by the broader PMSs
4: Research methodology	**5: Perspectives on BIM-AMs**	**6: Pilot Testing**
		
Introducing the chosen research methods including questionnaire, interview and the implementation of multiple AMs in practice	- Critical analysis of the BIM-AM, their similarities and differences - This includes the design process, the complexity and the range of measures	Initial testing of individual and multiple AMs in practice in association with a number of practices
7: Comprehensive testing	**8: Automated BIM-AM**	**9: Conclusions**
		
In association with Arup, applying three AMs to the same project and completed by six participants who have different BIM experience i.e. experts and graduates	Includes: - The need for automated AMs - The implementations of BIM-AM in practice	Current perspectives and future directions of BIM-AMs

4.1 Research design

Research design is the set of procedures and plans that inform the researcher's decision in regard to selected research methods and approaches undertaken for data collection and analysis. The selection of a specific type of research design is usually influenced by the nature of the research problem and the researcher's strategies to answer the research question (Creswell, 2013). In general, there are three major paradigms of research design, namely, qualitative, quantitative and a combination of the two i.e. mixed methods (Saunders, 2011). Each paradigm has its advantages and disadvantages. These three paradigms are discussed in the following.

Qualitative approach is 'a means for exploring and understanding the meaning individuals or groups ascribe to a social or human problem' (Creswell, 2009). In this approach, insights, perspectives, opinions, beliefs and understandings of people are investigated. The collected data (particularly in its raw form) might be unstructured, but tends to be 'detailed' in its scope and 'rich' in its content (Fellows & Liu, 2009). However, the objectivity of qualitative research often raises questions, especially by those with scientific backgrounds who sometimes criticise qualitative research for being 'too impressionistic and subjective' (Bryman, 2012).

Quantitative approach builds on 'scientific method', where the primary observations of theory and literature yield 'precise aims and objectives with hypotheses to be tested' (Fellows & Liu, 2009). It is therefore considered to be more trustworthy, consistent and objective when compared to qualitative research that is heavily based on subjective features (Baker, 2003). Generally, in quantitative studies, numerical data is collected through surveys and interviews to create statistical facts (Dawson, 2002).

The differences between the two approaches have been the subject of wide debate in the research method literature (Kilmann & Mitroff, 1976; Naoum, 2012; Smeyers, 2001). The fundamental difference between qualitative and quantitative research is particularly distinguished when applying 'words' (qualitative) instead of 'numbers' (quantitative), or using open-ended questions instead of closed-ended questions in the interviews (O'Dwyer & Bernauer, 2013). In addition, the aim of qualitative research is to provide an understanding of complex issues and it is therefore useful to answering 'why' and 'how' research questions. Conversely, the aim of quantitative research is to test pre-set hypotheses and generate generealisable outcomes. Therefore, quantitative research is mostly beneficial to answer 'what' questions (Marshall, 1996).

Mixed methods research bridges qualitative and quantitative research since elements of both approaches are employed (Creswell, 2013). This method is often applied in a single or multiple-phase study and uses different methods to collect data for the qualitative and quantitative parts of the research. A number of names have been given to this approach including multi-strategy (Bryman, 2004) or triangulation (Jick, 1979). The mixed methods research is based on viewing the research problems from different perspectives. In other words, rather than relying solely on one method, the mixed method approach acknowledges that the implementation of multiple methods and approaches will be beneficial for the quality and the completeness of the generated data (Denscombe, 2014). This approach is often applied when either the qualitative or the quantitative method independently is not enough to respond to the research problem. Mixed methods is complementary, pluralistic, comprehensive and aims to draw from the strengths of both qualitative and quantitative approaches whilst minimising their weaknesses (Johnson & Onwuegbuzie, 2004).

The research methods used to develop the existing sixteen BIM-AMs in the literature are not clear. Exceptions can be found in five instances where developers have discussed the adopted research methods to design their model. Table 14 presents the different research methods applied in past research on BIM performance measurement. In all these studies, a literature review is explored prior to selecting other supplementary methods. Some researchers, such as Succar, applied focus groups. Others, as Gao, relied on case studies from past literature to develop their model. However, each of the selected research methods has its advantages and disadvantages. Further explanation on previous AMs' design process will be given in Section 5.8.

Among social scientists, there is a growing consensus that the application of mixed methods enables more effective and advanced research programmes than through the use of a single research method. In this thesis, mixed methods research is used to explore the current landscapes and the future directions of BIM-AMs. Quantitative testing of existing AMs will be undertaken to explore the challenges and opportunities of BIM-AMs and to investigate the relationship between the participants' experience of BIM and the outcome of the assessments. In parallel, the understanding and views of BIM and BIM-AMs, will be further explored using qualitative interviews with experts in the BIM arena from academia, industry and government. Through the use of mixed methods research, it is hoped that this study will broaden the understanding of BIM-AMs by converging both qualitative and quantitative data.

Table 14 Applied research methods in coexisting BIM-AMs

BIM-AM	Applied research methods	Justification
BIM Maturity Matrix: (Succar, 2010a)	Literature reviews, introspection, experiential knowledge and focus groups	To develop the BIM Capability Stages and BIM Competency Sets. Focus groups to concepts of the matrix
BIM Excellence: Individual assessments: (Change Agents AEC, 2013)	Based on same knowledge infrastructure of BIM Maturity Matrix, with separate literature and varied methods applied to develop each of them	To develop the questionnaire survey of the BIM Excellence assessment
BIM Quick Scan: (Sebastian & Berlo, 2010)	Literature review Interviews. Quantitative and qualitative assessments	Interviews were conducted to decide which aspects of BIM should be evaluated
Characterisation Framework: (Gao, 2011)	Literature review Mainly multiple case studies, and interviews	To develop Characterisation Framework, choose measures
The Owner's BIMCAT: (Giel, 2013)	Literature review The Delphi Method: three rounds, electronic questionnaire via email	Rating the importance of competency factors for their AM

The research approach undertaken in this thesis is unique since it applies multiple methods to understand BIM-AMs from different perspectives. The research starts with a solid foundation that explores the evolution of AMs in the BIM domain and in other research disciplines. Previous researchers have directed little attention towards exploring AMs outside the BIM literature (exception is found in Succar's work). Also, they have been mostly restricted to limited comparisons of current AMs, which is essential to expand the knowledge surrounding the field of BIM-AMs as a whole and how it is likely to evolve in the future. This has been addressed in this thesis, in particular in Chapter 5. Each of the previous studies has its own advantages and disadvantages. For instance, in the Characterisation Framework, Gao provides a substantial contribution to the BIM measurement domain but the study, PhD thesis, is entirely built on past projects' data in order to develop the framework. Gao did not apply the framework in the industry, which is crucial to investigate the framework's validation, applicability and replicability. However, Gao relied on interviewees opinions for validation.

4.1.1 Literature review

A sophisticated and comprehensive literature review is the foundation for substantial, robust and effective research (Boote & Beile, 2005). The potential of an effective literature review is further explained by Webster and Watson (2002) who note that:

> "A review of prior, relevant literature is an essential feature of any academic project. An effective review creates a firm foundation for advancing knowledge. It facilitates theory development, closes areas where a plethora of research exists, and uncovers areas where research is needed."

The literature related to this research addresses two major areas. The first focuses on the larger and ongoing dialogue of performance measurement systems in different disciplines (Chapter 2). The second focuses in particular on BIM-AMs and delineates the boundaries of the performance measurement research field (Chapter 3). In both chapters, the key concepts of AMs, and their overall development, opportunities and challenges are investigated. The literature review has identified critical gaps of current BIM-AM knowledge which formed the foundation for this research. In addition, it shed light on how BIM-AMs have been influenced and shaped by the wider research field of AMs, it also explored what research methods previous researchers have used in the BIM measurement literature.

4.1.2 Comparative method

The comparative method analyses the casual connections and relationships between phenomena. 'Comparison is one of the crucial conceptual processes making the world intelligible' (Caramani, 2009). It is a fundamental tool of analysis that helps researchers to focus on similarities and differences through case studies (Collier, 1993). This exploratory approach is often used to compare and examine research cases as a whole (Ragin, 1989), establish generalisations across variables (Lijphart, 1971) and 'discover a common thread or level of description which cuts across group lines' (Suchman, 1964). This method is commonly used in performance measurement literature; as in the building environmental AMs (Cole, 2006; Schweber & Haroglu, 2014; Todd et al., 2001). However, it is less common in BIM-AMs research.

The comparative method was applied in this research to compare the features and relationships between the existing AMs (Chapter 5) and to provide a correlational analysis of BIM-AMs as whole, their evolution and the relationships between them.

4.1.3 Multiple case studies

Case study is a valuable research method that has been applied broadly in different disciplines such as, business, management, marketing, education, medicine and psychological research (Gerring, 2006). It is 'an intensive study for single unit for the purpose of understanding a larger class of (similar) units' (Gerring, 2004). Case study is a research method that 'investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident' (Yin, 2003). This is perhaps one of the most recognisable definitions of Case Study and has been widely cited in research method literature.

Generally, case study research includes either a single case study or consists of a multiple-case studies (Tellis, 1997). Selecting one of these two types depends on both the research question and constraint of finding more than one case study (since it is sometimes difficult to find industry professionals who are willing to collaborate with researchers due to time constraints and workloads). If the studied topic involves a part of the social science which is rarely accessible to the researcher (not the case in BIM-AMs), then a single study is likely implemented, as it offers an in-depth investigation of the topic. If the studied area will benefit from comparing contrasted and (or) complementary studies, then multiple case studies are employed (Yin, 2015). 'Thick' or detailed single case studies have played significant role in different disciplines, since they enable a comprehensive understanding of an individual case study. However, their main limitation is that they are 'very difficult to engage in any form of generalisation'(Rihoux & Ragin, 2008).

Since the development and the implementation of BIM-AMs are still an emerging phenomenon, a case study method is applied in this research to better understand BIM-AMs within some real life-context, for instance, application in practice. However, rather than relying on a single case study, multiple Case Study Project (CSPs) are undertaken, which offer more compelling results. In this approach, multiple CSPs are examined to understand the similarities and differences between them. The value of CSPs increases significantly when applying multiple studies, since it identifies patterns across cases (Woodside, 2010), and generates more powerful and more credible results than a single case study. Their application also enables a wider array of evidence when compared to single cases (Yin, 2011).

4.1.4 Interviews

Interviews are a data collection method that rely on participants' answers to researcher's questions. Interview has become 'one of the most widespread knowledge-producing practices across the human and social sciences' (Brinkmann, 2014). It has the potential to open up interviewees' interpretation of questions based on their knowledge, understanding and experiences (Bagnoli, 2009). In general, there are three fundamental types of research interviews based on their structure: structured, semi-structured and unstructured. Ritchie et al. (2005) provide a detailed comparison between the three types.

In **structured interviews**, a set of predetermined questionnaires are asked with little or no follow-up questions for further investigation. Therefore, structured interviews are relatively quick and easy for an interviewer to undertake, but they are 'quite limiting'. They are particularly useful when comparison is required across numerous interviews, since the same questions are asked to each participant (Wilson, 2012).

In contrary, **unstructured interviews** require no prearranged questions nor do they reflect any preconceived theories or ideas. They include little or no organisation and simply start with a general opening question, such as 'what is BIM?' The interview will then evolve based on the initial responses. Unstructured interviews are usually time-consuming, difficult to manage and to participate in, since the lack of predefined questions might result in little guidance on what to talk about (Gill et al., 2008). Because the conversation could go anywhere, comparison across multiple interviews is more difficult. However, they are most helpful where significant in-depth understanding of particular phenomenon is required (Zhang & Wildemuth, 2009).

Semi-structured interviews offer a more flexible approach than the structured interviews. The researcher has some pre-specified open ended questions and in parallel probes further topics of interest as the interviewee responds. Semi-structured interviews can generate 'powerful data that provide insights into the participant's experiences, perceptions or opinions' (Peters & Halcomb, 2015). Divergence from the prepared questions might be required to draw more details on an idea (Britten, 1995). Continuing with the same example above 'what is BIM', participants might be asked additional questions on the topic such as 'what is the reason for the uncertainty surrounding the definition of BIM?' and (or) 'what do you mean by 4D and 5D?'

A semi-structured interview approach is implemented in this research for two major reasons. Firstly, because this approach enables higher levels of flexibility for both the interviewer and the interviewee to probe more details when discussing BIM without being strictly limited to a pre-established set of questions. Secondly, due to the varied educational and professional backgrounds of the sample group, participants might have different perspectives and insights on BIM according to their experience. This requires further discussion and might lead to the discovery or elaboration of highly influential new paths that have not been considered before (Kajornboon, 2005). Such findings might be achieved by asking follow-up questions which may not have emerged in structured interviews.

In semi-structured interviews, it is possible for the researcher to develop and adjust the research questions according to the development of the research (Denscombe, 2014). Initial interviews were more exploratory than later interviews. Preliminary interviews included wider questions of BIM, such as, the definition of BIM, its benefits and challenges, the businesses' BIM vision and the ways companies were training their staff in regard to BIM. Later interviews, however, were more consistent, narrowed, and focused particularly on BIM-AMs, their opportunities and challenges. However, in all the eleven interviews, open-ended questions were used to explore the participants' views and opinions.

Eleven participants were contacted via email and LinkedIn to arrange a convenient time for the interview. When invited, participants were informed that each interview would require 20 to 60 minutes. All interviews were recorded (except with Interviewee 6) and then transcribed. Dates of interviews, the position and organisation of interviewees are presented in Table 15. The interviews were carried out via web-conferencing (as with Interviewees 3, 5, 8, 10 and 11) or through personal face-to-face interviews carried out in Bath and London (as with Participants 1, 2, 6, 7, and 9).

At the start of each interview, a brief introduction to the research was provided. By the end of each interview, participants were asked if they have any more thoughts or suggestions to add. This gave them the opportunity to highlight additional points that they think they are important and have not been noted by the interviewer (Kvale, 1996). The group of interviewees is relatively homogenous in that all participants have extensive knowledge of BIM but from different perspectives. The sample of interviewees was therefore varied with experts having different backgrounds from several leading institutions to maximise the richness of data.

Table 15 BIM experts interviewed in this research

Location	**Interviewee**	**Date**	**Position**
1) UK	Interviewee 1	15.01.2014	CAD technician
2) UK	Interviewee 2	05.02.2014	A BIM manager and Head of Corporate R&D at a global property and construction constancy
3) UK	Interviewee 3	28.02.2014	Head of BIM at an international consultancy and construction company and head of BIM implementation in BIM Task Group, Cabinet Office
4) Australia	Interviewee 4	03.03.2014	Conjoint Senior Lecturer at a university in Australia
5) US	Interviewee 5	03.03.2014	Executive vice president at a global property and construction consultancy
6) UK	Interviewee 6	06.03.2014	BIM Regional Ambassador at CIC and a member of the construction Strategy Group to advise the RIBA
7) UK	Interviewee 7	06.03.2014	Senior architect and progressive design architect
8) UK	Interviewee 8	27.03.2015	Senior lecturer at the School of Civil and Building Engineering
9) UK	Interviewee 9	07.04.2015	BIM development manager in an engineering consultancy
10) US	Interviewee 10	06.05.2015	Strategist for the Transformation of the Facilities and Infrastructure Industries
11) UK	Interviewee 11	02.06.2015	Capital Programme manager

4.1.5 Survey

The survey is a research method that studies a sample of the population through a structured questionnaire (Bergman, 2008). It offers a quantitative or numeric description of attitudes, trends and opinions about some aspects of the participating population (Fowler Jr, 2013). From the collected results of the sample, a researcher can generalise or make claims about the population (Creswell, 2009). Different types of data collection approaches can be applied when undertaking a survey, face-to-face interview, or through telephone, email or mail surveys (Wright, 2005).

'Sample surveys are one of the most important basic research methods in the social science' (Marsden & Wright, 2010). They have been applied in a wide range of research fields including education, public health, political science, sociology and economics. In the BIM research field, they have been widely applied to generate quantitative data on BIM. For instance it has been used to investigate the state of BIM implementation in the industry (Cao et al., 2015), to identify the benefits and barriers of BIM (Isaksson et al., 2016; Yan & Damian, 2008) and to explore different themes on BIM implementation in the UK's AEC industry, as in the yearly National BIM Survey (RIBA Enterprises, 2012, 2013, 2014, 2015).

The survey method has also been applied in the BIM-AM literature. Giel (2013) used a questionnaire to assess the BIM implementation status in the U.S. industry and to identify the appropriate measures for their evaluation framework. Similarly, Lee and Won (2014) used a survey approach to determine the key performance indicators to include in their proposed assessment.

In this thesis, a structured survey questionnaire is used to examine the knowledge of those engaged in the BIM debate on a set of issues related to AMs i.e. awareness of AMs and the importance of measuring BIM. When developing the questionnaire, several considerations have been addressed. This included selecting questions that matched the research aim and objectives, developing a questionnaire that was clear and easy for participants to complete (Kemper et al., 2003) and avoiding leading questions (King et al., 1998).

The questionnaire was distributed to 61 participants between July and August 2015. Data collection was carried out via email, by distributing paper questionnaires at 'The Future of BIM: Looking beyond 2016' conference at the University of Salford, and by visiting two engineering companies, both based in the UK (Table 16). A total of 50 questionnaires were returned (completion rate of 81%). However, 9 of those questionnaires were excluded because the respondents had no previous BIM experience. Therefore, the number of questionnaires included in the study was 40. The respondents had different levels of BIM experience ranging from six months to twelve years. They were from several disciplines including architects, academics, researchers, BIM managers and technicians.

Table 16 Collected questionnaires

Data collection	***Number of distributed questionnaires***	***Completed questionnaires***	***Included questionnaires***
'The Future of BIM' Conference	*27*	*27*	*21*
Email	*15*	*4*	*4*
Arup, London, UK	*13*	*13*	*13*
Buro Happold, Bath, UK	*6*	*6*	*2*
Total	*61*	*50*	***41***

4.2 Conclusion

As presented in Section 4.1, there are three main research approaches qualitative, quantitative and mixed methods. In addition, there are different research methods that can be applied depending on the research question and aim. Researchers in BIM-AMs have implemented different research approaches to develop their assessments (Section 4.2). Each has its unique way of collecting data, and analysing it and each approach has its own advantages and disadvantages. The design process of past AMs will be further explored in Section 5.8.

In this research, mixed research methods were applied. The research process, including the aim and objectives and data collection methods to achieve these objectives, is exhibited in Figure 18. The figure also shows where each method is being used and how each chapter builds on the previous one.

After discussing the adopted research methods, Chapter 5 will offer an overall view of the research field of BIM-AMs as a whole.

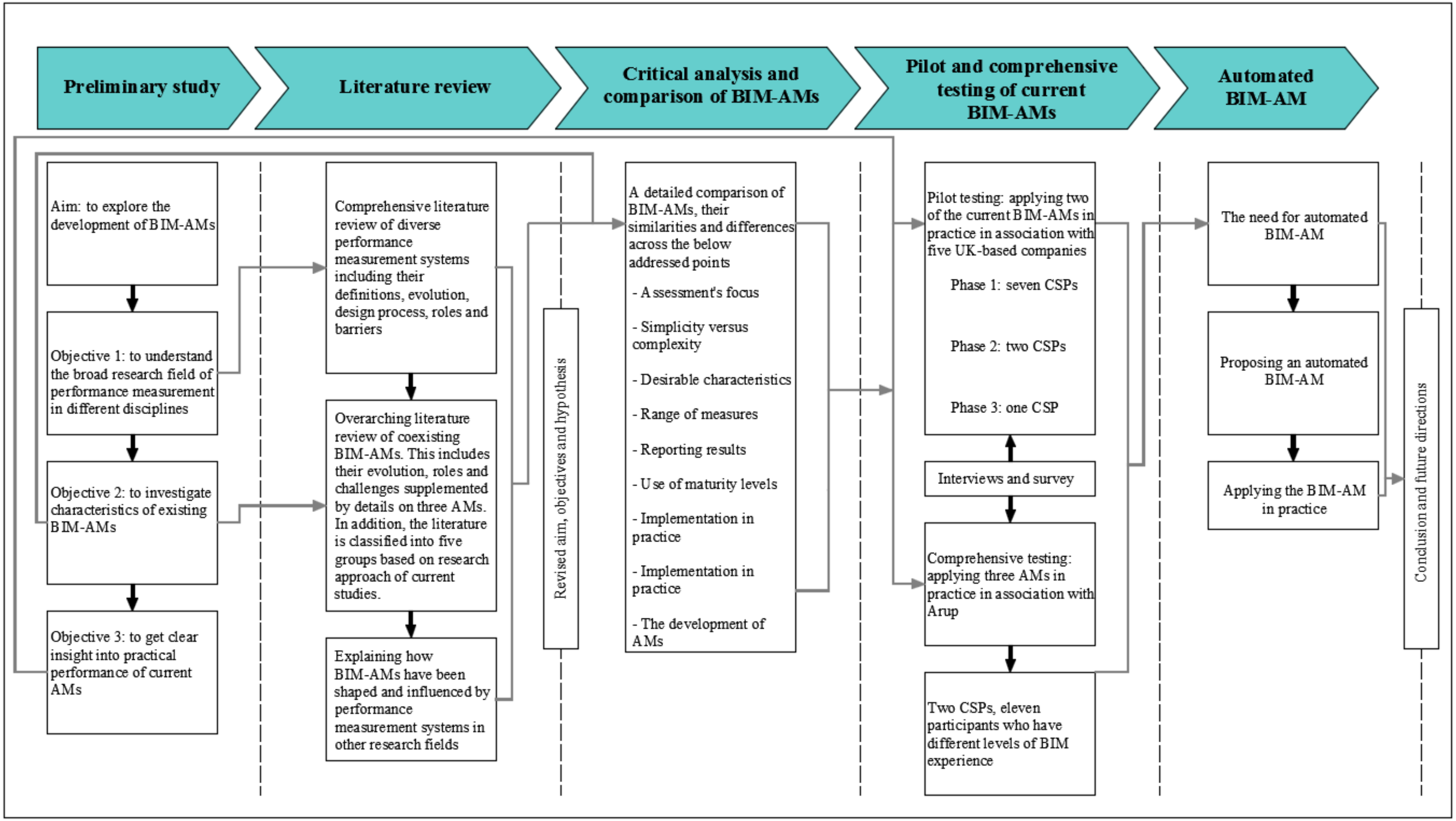
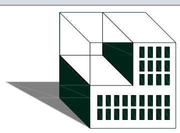
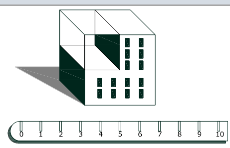
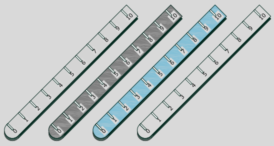
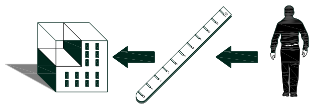
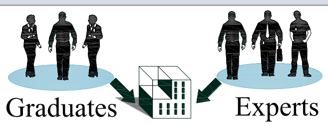
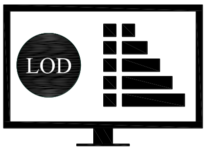


Figure 18 Research process

5 Perspectives on current BIM-AMs

Despite the increasing development of AMs, it has been observed in Chapter 3 that the field as a whole is still under-examined with substantial challenges to be addressed. Particularly, the lack of a comprehensive research agenda of AMs and the absence of side-by-side comparison of existing models. Consequently, Chapter 5 identifies the critical characteristics of existing AMs (see Appendix A). The assessment focus and the use of maturity levels in each AM are discussed and analysed in detail before three AMs are applied in practice in Chapter 6 and 7.

1: Introduction	**2: PMSs**	**3: BIM-AMs**
		
Main questions included: What is BIM? What is the need for BIM-AMs?	Includes: - Brief history of the broad PMSs, their definitions - PMSs roles and barriers - Sample of PMSs	- Explains the wide range of BIM-AMs, their evolution, opportunities and challenges - Investigates how BIM-AMs have been informed by the broader PMSs
4: Research methodology	**5: Perspectives on BIM-AMs**	**6: Pilot Testing**
		
Introducing the chosen research methods including questionnaire, interview and the implementation of multiple AMs in practice	- Critical analysis of the BIM-AM, their similarities and differences - This includes the design process, the complexity and the range of measures	Initial testing of individual and multiple AMs in practice in association with a number of practices
7: Comprehensive testing	**8: Automated BIM-AM**	**9: Conclusions**
		
In association with Arup, applying three AMs to the same project and completed by six participants who have different BIM experience i.e. experts and graduates	Includes: - The need for automated AMs - The implementations of BIM-AM in practice	Current perspectives and future directions of BIM-AMs

5.1 Assessment's focus

BIM-AMs have been designed for different purposes and each has its own aim, objectives and agenda. Collectively, they can be classified into four main groups according to their evaluation focus i.e. whether the AM evaluates projects, organisations, teams or individuals (Figure 19).

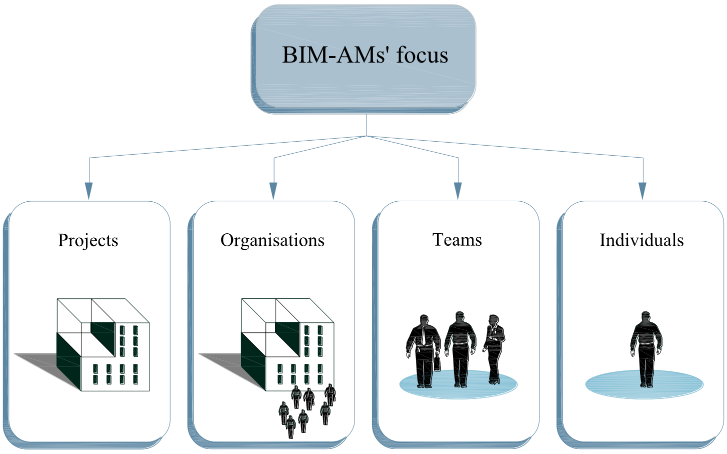


Figure 19 BIM-AMs' focus

A considerable number of AMs have been developed to evaluate BIM in organisations, with eleven AMs compared to five assessing projects whilst far less research has been directed towards evaluating BIM across individuals and teams with only three and one AMs respectively (Table 17). Some of the current AMs, however, offer multiple versions, with different evaluation focus. The most recent AM, for instance, the BIM Level 2 BRE certification has two versions: BIM Level 2 Business Systems Certification (organisational level) and BIM Level 2 Certified Practitioner Scheme (individual level) (BRE, 2015a, 2015b). Another instance can be found in BIM Excellence where its developer suggests four levels of assessments, namely, individual assessment, organisational assessment, project assessment and team assessment (Change Agents AEC, 2013).

There are substantial differences between the four forms of assessments, mainly the type of tracked measures and the aim of the AM. AMs of organisations assist the Architecture, Engineering and Construction (AEC) industry to evaluate readiness of organisations when implementing BIM (CIC, 2013). Consequently, they provide an overarching framework to translate the organisation's strategic objectives into a set of measures. These measures are not designed to evaluate any particular case study project, but rather to emphasise on the BIM maturity levels of the company as a whole. Examples of the evaluated measures include BIM visions and objectives, roles and responsibilities, training and education.

Assessing BIM in projects was firstly suggested by the NIBS when releasing the NBIMS-CMM (NIBS, 2007). Such AMs help organisations to manage their BIM utilisation. They are designed to enable managers minimising uncertainty and concentrating financial and human resources on critical issues (Kam, 2015). Generally, they are applied to each project as a unique case regardless of the organisation's maturity level. Some of the measures applied in projects' AMs are the data exchange method between project members and teams, the Level of Detail (LOD) of model's element, model use, and the software applied at each phase of the project. Despite these differences, there are many common areas of measurement between AMs of organisations and projects. More recently a number of researchers have called for assessments that cover both organisations and projects (Jupp, 2013; Sebastian & Berlo, 2010).

Table 17 Assessment focus of current BIM-AMs

No	BIM-AM	**Organisation**	**Project**	**Individual**	**Team**
1	NBIMS-CMM		✓		
2	BIM Excellence	✓	✓	✓	✓
3	BIM Proficiency Matrix	✓			
4	BIM Maturity Matrix	✓			
5	BIM Quick Scan	✓			
6	VICO BIM Score	✓			
7	Characterisation Framework		✓		
8	CPIx BIM Assessment Form			✓	
9	Organisational BIM Assessment Profile	✓			
10	VDC Scorecard		✓		
11	bimSCORE		✓		
12	The Owner's BIMCAT	✓			
13	BIM Maturity Measure		✓		
14	Goal-driven method for evaluation of BIM project		✓		
15	The TOPC evaluation criteria	✓			
16	BIM Level 2 BRE Certification	✓		✓	

5.2 Simplicity versus complexity

AMs are generally developed to reflect either a model simplicity or complex reality, each has its own pros and cons. The levels of simplicity and complexity amongst current BIM-AMs differ to a great extent and are dependant on the range and type of measures included. Oversimplifid models are ususally focused and narrow requiring short time to complete, which in turn attracts more attention from professionals. They tend to include a few measures refelecting particular aspects of BIM rather than representing the complexity of the domain. They are therefore criticised for not offering sufficient information for users (De Bruin et al., 2005). Currently, half of the AMs consist of fewer than thirty measures (Figure 20). The NBIMS-CMM, for instance, consists of eleven measures (NIBS, 2015). Participants completing the assessment are required to provide only eleven answers which might take in practice from 15 to 30 minutes. The model has been criticised, however, for covering specific areas of BIM rather than evaluating its multifaceted aspects (Kam et al., 2013b).

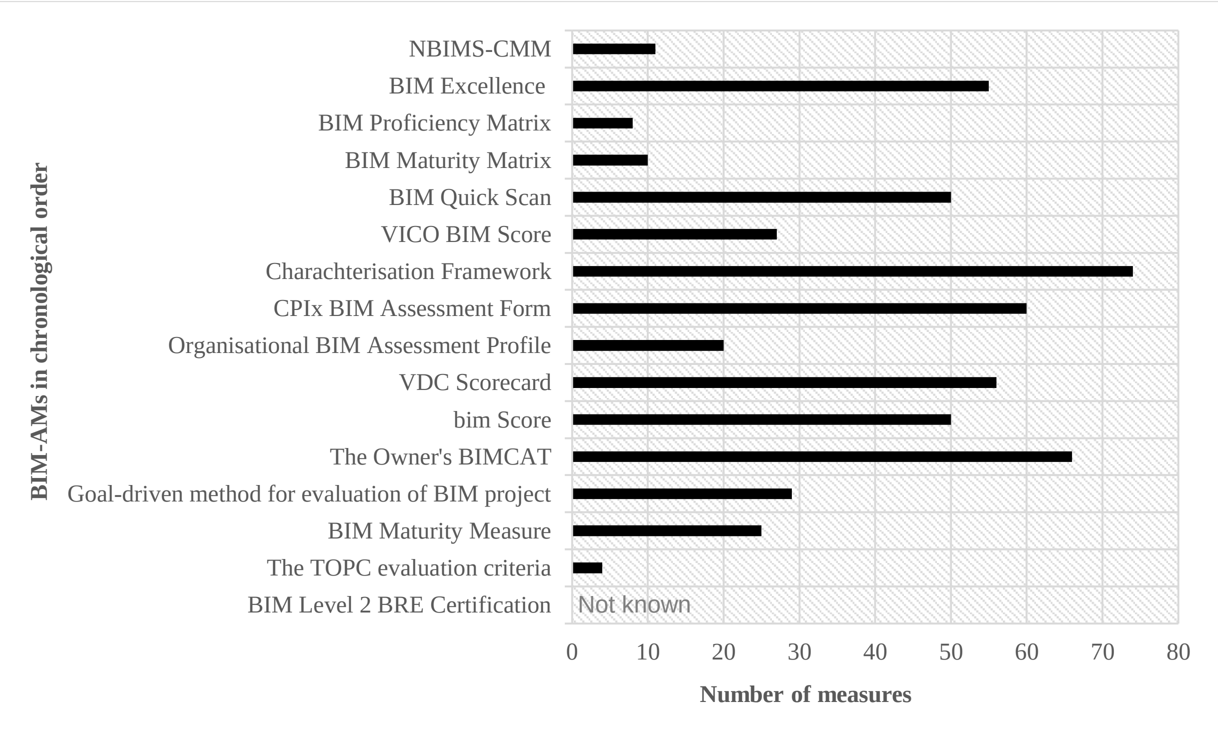


Figure 20 Simplicity versus complexity of current BIM-AMs (from older, to most recent)

Conversely, complex AMs offer more comprehensive and more detailed means for BIM performance measurement. The Characterisation Framework (Gao, 2011), presented in Chapter 3, includes the largest number of measures amongst the existing AMs with 74 measures; nearly seven times the measures of the NBIMS-CMM. This is followed by the Owner's BIMCAT (Giel, 2013) and the VDC Scorecard (Kam, 2015) with 60 and 56 measures respectively. One of the main criticism of detailed models is that they limit interest since they report extensive measures and require a long time to complete. When CIFE researchers assessed 108 case study projects using the VDC Scorecard, the average proportion of completed questions was 72% (Kam et al., 2013b). Indeed, many organisations identify more measures than they can possibly track and use. Researchers, therefore, should highlight the most critical measures that help focusing the strategic vision of the AM. Developers of the Balanced Scorecard (BS) argue that fifteen to twenty measures are generally 'enough' when designing a measurement system (Kaplan & Norton, 2004). This applies only to one of the current BIM-AMs, the Organisational BIM Assessment Profile which consists of twenty measures across six BIM areas (CIC, 2013).

When selecting the complexity level of the AM and the number of its measures, researchers have to address four critical points (De Bruin et al., 2005). These points are linked to the purpose and the need for the model (why), the use of the model (how), the involved participants (who) and the desired outcome of the model (what). In other study in the building environmental AMs, the range of applied measures is argued to be influenced by:

- The practicality and cost directed towards the investment in AM (since greater efforts are required when having more measures)
- The ability to provide reliable and repeatable assessments with consistent results. As a result, different assessors of the same project should produce similar evaluations. Greater differences can occur if the AM includes qualitative measures where assessors reply on personal judgement to complete the assessment
- The general agreement of the measures and the confidence in their importance
- The ability to translate the outcome of the AM into understandable results

Types and range of measures tend to reflect critical points defined by its developer(s). However, the main challenge when designing AMs is not only linked to the comprehensiveness of the AM but also to the difficulty of measuring some of its measures. A detailed model might limit interest and result in incomplete assessments but also it can be practical and quick to complete if it offers an overarching approach and a user-friendly method. Equally, a simplified model might be difficult to complete if the used terms are undefined and if the model is not structured. However, if designed well it might enable coherent and focused outcomes that respond to the aim and objectives of its developers.

5.3 Desirable characteristics of BIM-AMs

“What does a well-designed BIM-AM look like?” is one of the main questions to be addressed when developing AMs. Despite the high level of research and industrial interest in measuring the implementation of BIM, only a few scholars seek to answer this question. Succar et al. (2012) suggest that the measures of BIM-AMs should be:

- **Accurate** and well-defined to provide a high level of precision
- **Applicable** by different AEC stakeholders and across different phases of the project
- **Attainable** and achievable
- **Consistent** results should be obtained when completing the AM by different assessors
- **Cumulative** where deliverables result in logical progressions
- **Flexible** across diverse markets and different organisational scales
- **Informative** by providing feedback on the current process and directions for future improvement
- **Neutral** (non-proprietary)
- **Specific** in terms of requirements desired by the construction industry
- **Universal** and applied across different practices in different countries
- **Usable** and easily implemented

These characterisations have informed the development of Succar’s AMs and later they were picked up by other researchers when developing their own models (Sebastian & Berlo, 2010). Furthermore, Gao (2011) offers a different angle and notes that a good AM should consider three aspects. Firstly, AMs should have the documentation power to offer the ability to organise projects information in a structured, sufficient and consistent way. Secondly, AMs should enable comparisons across different projects. Thirdly, AMs have to be based on methodological rigor and should be generalised and validated through implementation in case studies. CIFE researchers also identify four criteria for assessments to overcome the limitations of previous AMs (Kam et al., 2013b). According to them, AMs should be **holistic** to cover comprehensive areas rather than focusing on fractional elements of BIM, **quantifiable** in which the assessment consists of objective measures to provide accurate results, **practical** in a way that AEC professionals should find the implementation of the model actionable, meaningful and practical assessment and **adaptive** by responding to the rapid changes in industry. Recently, Chen (2015) follows a different approach which considers the users of the tool and the way the tool is used.

Accordingly, AMs should be self-applied, adoptable by decision makers and usable by clients during the tendering and prequalification stages.

Observations of these four instances show that there has been no consensus on what is required to develop a well-designed AM and each suggests a different approach. However, all these studies chose to explore issues linked to practicality and the usability of the AM, which is important, but without focusing on where to extract the measures from. In contrary, the top recommendation found in a comprehensive analysis of ten papers reported in section 2.8 suggests that measures should be derived from strategy (Neely et al., 1997). Indeed, comparison between the above reported characterisations in the BIM domain and the 22 recommendations in the broader field of business management shows areas of similarities and differences. They are similar because both fields suggest that 'good' AMs should be consistent, precise, specific, clearly defined and informative. They are also different because most of the reported characterisations by Neely et al. (1997) are not noted in the BIM studies. Some of these substantial recommendations that impacts on BIM-AMs suggest that measures should be simple to understand, reflect the business process, provide simple and fast consistent feedback and enable automated data collection whenever possible. These themes should help to improve the evolving field of BIM-AMs.

5.4 Range of BIM-AMs' measures

Selecting the appropriate measures (variables, indicators, factors or areas of measurement) to evaluate is a substantial part of designing any AM, because "what gets measured and reported gets attention" (Hatry, 2006, p. 59), and because captured measures can be used to inform decision making (Neely et al., 1997). As professionals and researchers have tried to overcome the limitations of previous AMs, they have focused on introducing new strategies of BIM measurement. Rather than focusing on a particular side of BIM, they have addressed more diverse measures and more integrated perspectives that are drivers for future BIM performance. Currently, the variety of AM's criteria that are relevant to BIM is enormous. Together, AMs have covered over 200 different measures. In most AMs, these measures have been structured into main categories (sections, chapters or areas) according to their similarities. Each category reflects a particular angle of BIM, for instance, some of them are process-oriented as in the BIM Maturity Matrix and the Organisational BIM Maturity Profile, and others are technology focused as in the VDC Scorecard. Table 18 presents a sample of the major areas covered in twelve AMs and how each AM has shed the light on diverged areas of evaluation.

Table 18 Sample of the main areas of measurement in BIM-AMs

NBIMS-CMM	**BIM Maturity Matrix**	**Characterisation Framework**
1- Data Richness 2- Life Cycle Views 3- Roles or Disciplines 4- Change Management 5- Business Process 6- Timeliness/Response 7- Delivery Method 8- Graphical Information 9- Spatial Capability 10- Information Accuracy 11- Interoperability/IFC support	1- Technology (Software, Hardware and Network) 2- Process - Infrastructure (Products and Services, Human Resources and Leadership) 3- policy (Regulation, Contractual and Preparatory)	A- Context B- Implementation C- Performance Impact
BIM Excellence Individual Assessment	**BIM Quick Scan**	**CPIx- BIM Assessment Form**
1- Technical 2- Operation 3- Functional 4- Implementation 5- Administration 6- Supportive 7- Research and Development 8- Managerial	1- Organisation and Management 2- Mentality and Culture 3- Information structure and information flow 4- Tools and applications	1- Design Construction Intelligent 3-D Modelling 2- Life cycle cost and life cycle assessment 3- Facilities Management 4- Quantity take-off, Costing 5- Sales/Visualisation 6- Safety Planning 7- Clash Detection 8- 4D-Scheduling 9- Production BIM 10- Procurement 11- Supply Chain Management 12- Simulations, Energy, Fire etc.
BIM Proficiency Matrix	**Vico BIM Scorecard**	**Organisational BIM Assessment Profile**
A- Physical Accuracy of Model B- IPD Methodology C - Calculation Mentality D - Location Awareness E - Content Creation F - Construction Data G - As-Built Modelling H- FM Data Richness	1- Portfolio and Project Management 2- Cost Planning 3- Cost Control 4- Schedule Planning 5- Production Control 6- Coordination 7- Design Team Engagement	1. Strategy 2. BIM Uses 3. Process 4. Information 5. Infrastructure 6. Personnel
VDC Scorecard/bim SCORE	**The Owner's BIMCAT**	
1- Planning 2- Adoption 3- Technology 4- Performance	1- Operational Competencies 2- Strategic Competencies 3- Administrative	

To specify the top evaluated criteria across the varied AMs, all measures (accommodated in sub-areas) have been extracted and listed in one table to identify mutual areas of evaluation. It should be noted that stating common measures is controversial since some of the measures are evaluated in multiple AMs but are introduced in different terminologies. Observations of all measures shows that the most popular five measures across the 16 AMs are, in order, Level of Detail (LOD), visions and goals, technology and model use (Table 19).

LOD is particularly important in the field of BIM and is an evolving topic in both academic and industry. Currently, it is the highest examined measure since it is evaluated in eight AMs (sometimes it is being referred to as either data richness or level of development). LOD has been measured by applying different approaches in which all of them are highly dependent on subjective judgement. It is defined as the 'the maximum amount of information and geometry authorised for use by others' (Harvard UCMC, 2013, p. 12). This includes the geometrical (e.g. 2D and 3D drawings) and non-geometrical information which should be attached to the BIM model. LOD was initially defined by the American Institute of Architects (AIA) who introduced five LODs (100, 200, 300, 400 and 500) to enable practitioners assigning the model elements to certain LOD at certain stage of the project life-cycle (AIA, 2008). LOD will be discussed with further details in Chapter 8.

The second joint most common measures are 'visions and goals', technology' and 'data exchange', which have been evaluated in seven AMs. These three areas are evaluated in seven out of the sixteen AMs. However, similar to the LOD, these measures are interpreted differently by different researchers. The third most highlighted measure is 'model uses', evaluated in six AMs, and referring to the way the BIM model is being used for different purposes, such as documentation and visualisation during different stages of the project's life-cycle. Table 19 shows the five most evaluated measures across current BIM-AMs, which reflect the most critical BIM areas addressed in the BIM measurement literature.

Defining key common measures across the 16 AMs is still problematic. Many scholars have not clearly defined or explained their measures, making it difficult to explore similarities and differences. Another unresolved problem is deciding what type of performance information should be tracked. Several developers of the existing AMs have extensively discussed the methodological criteria behind selecting their measures.

Table 19 Most commonly evaluated measures across the 16 BIM-AMs, with exact terminology

BIM-AM	**Data richness**	**Visions and goals**	**Technology**	**Data exchange**	**Model use**
NBIMS-CMM	Data richness	-	-	Interoperability + Delivery Method	-
BIM Excellence	-	-	Technical	-	-
BIM Proficiency Matrix	Data richness	-	-	-	-
BIM Maturity Matrix	-	Leaderships' BIM visions	Technology	Network	Software usage
BIM Quick Scan	-	Vision &strategy	Tools and applications	Internal and external information flow	Use of modelling
VICO BIM Score	-	-	-	-	-
Characterisation Framework	Level of detail	Vision into Implementing BIM		Data Exchange	Model Uses
CPIx BIM Assessment Form	-	-	-	-	-
Organisational BIM Assessment Profile	Level of development	BIM vision & Objectives/ goals	Software and hardware	-	-
VDC Scorecard	Level of detail/development	Management Objectives	Technology	Data Sharing Method	Model uses
bim Score	Level of detail/development	Management Objectives	Technology	Data Sharing Method	Model uses
The Owner's BIMCAT	Data richness/LOD	Goals/Objectives	Technology	-	-
BIM Maturity Measure	Level of development	-	-	Common data environment	Drawings
Goal-driven method for evaluation of BIM project	-	-	-	-	-
The TOPC evaluation criteria	-	-	-	-	-
BIM Level 2 BRE Certification	Not known				
Total number of AMs measuring this	8	7	7	7	6

5.5 Reporting results

A clear approach to communicating the results of AMs is essential to inform decisions and to translate outcomes into meaningful dialogue (Cole, 1998). Results generally reflect the structuring criteria of the assessment, its main areas and sub-areas and therefore it also reflects the simplicity or complexity of the model. In current BIM-AMs the forms of results used vary to a great extent and range from tables and radar charts to reports and certifications. Some of the AMs, however, apply one or a combination of these diverse forms. In the Organisational BIM Assessment Profile (CIC, 2013), the summary calculation of all measures will be reported in a table that presents not only the current maturity levels of the six major areas but also the target levels (Table 20). Separately, each of the six main areas will be documented with its sub-areas in both a table and a radar diagram (Figure 21 shows the Strategy element with its five measures).

Table 20 Summary calculation in the Organisational BIM Assessment Profile (CIC, 2013)

BIM Planning Element	Current Level	Target Level	Total Possible
Strategy	44%	68%	25
BIM Uses	20%	50%	10
Process	20%	50%	10
Information	27%	47%	15
Infrastructure	33%	53%	15
Personnel	20%	40%	25

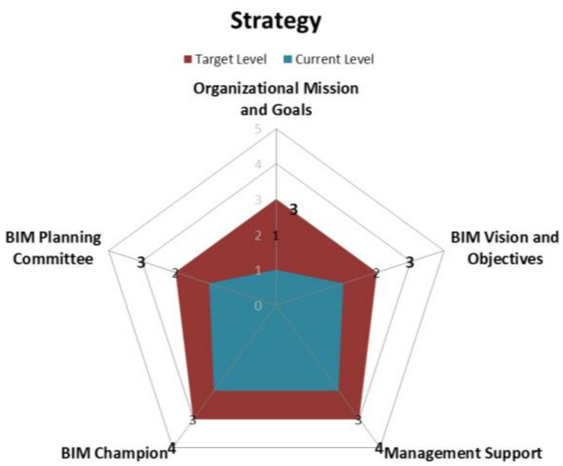


Figure 21 Calculation of the Strategy element (CIC, 2013)

Different AMs apply different forms when reporting results as illustrated below. However, radar charts are commonly applied in many AMs including the NBIMS-CMM, BIM Quick Scan, the Organisational BIM Assessment Profile, the VDC Scorecard and the Owner's BIMCAT. Some of these reports, however, provide more details than others. In the VDC Scorecard each element, such as the prefabrication indicator (Figure 22), is broken down to its sub-areas, similar to what is found in the Organisational BIM Assessment Profile.

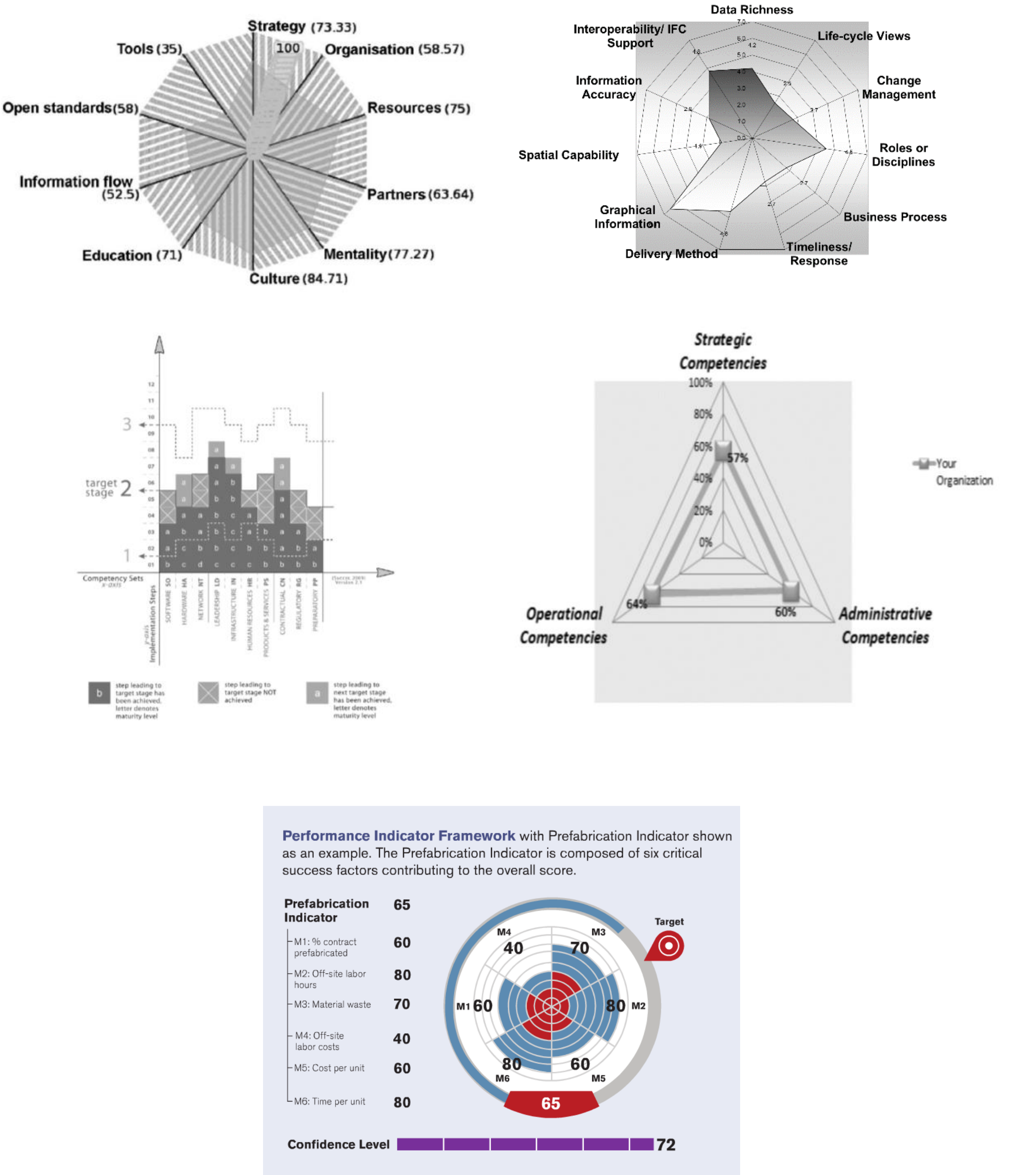


Figure 22 Forms of reporting results, from top left clockwise, in the BIM Quick Scan (Sebastian & Berlo, 2010), NBIMS-CMM (NIBS, 2007), the Owner's BIMCAT (Giel, 2013), the VDC Scorecard and the BIM Maturity Matrix (Succar, 2010a)

The BIM Maturity Measure (BIM-MM) is perhaps one of the AMs which provides a relatively detailed approach when reporting results. Overall scores of different disciplines are presented but without being directed to a specific level of maturity (Arup, 2014). Figure 23 illustrates the reporting form of BIM-MM, the above side of the report shows the Primary Score, which is the average scores of the Project and the first four evaluated disciplines, usually Structures, Electrical and Public health. The below side of the report presents the scores of these disciplines individually as well as the scores of included measures.

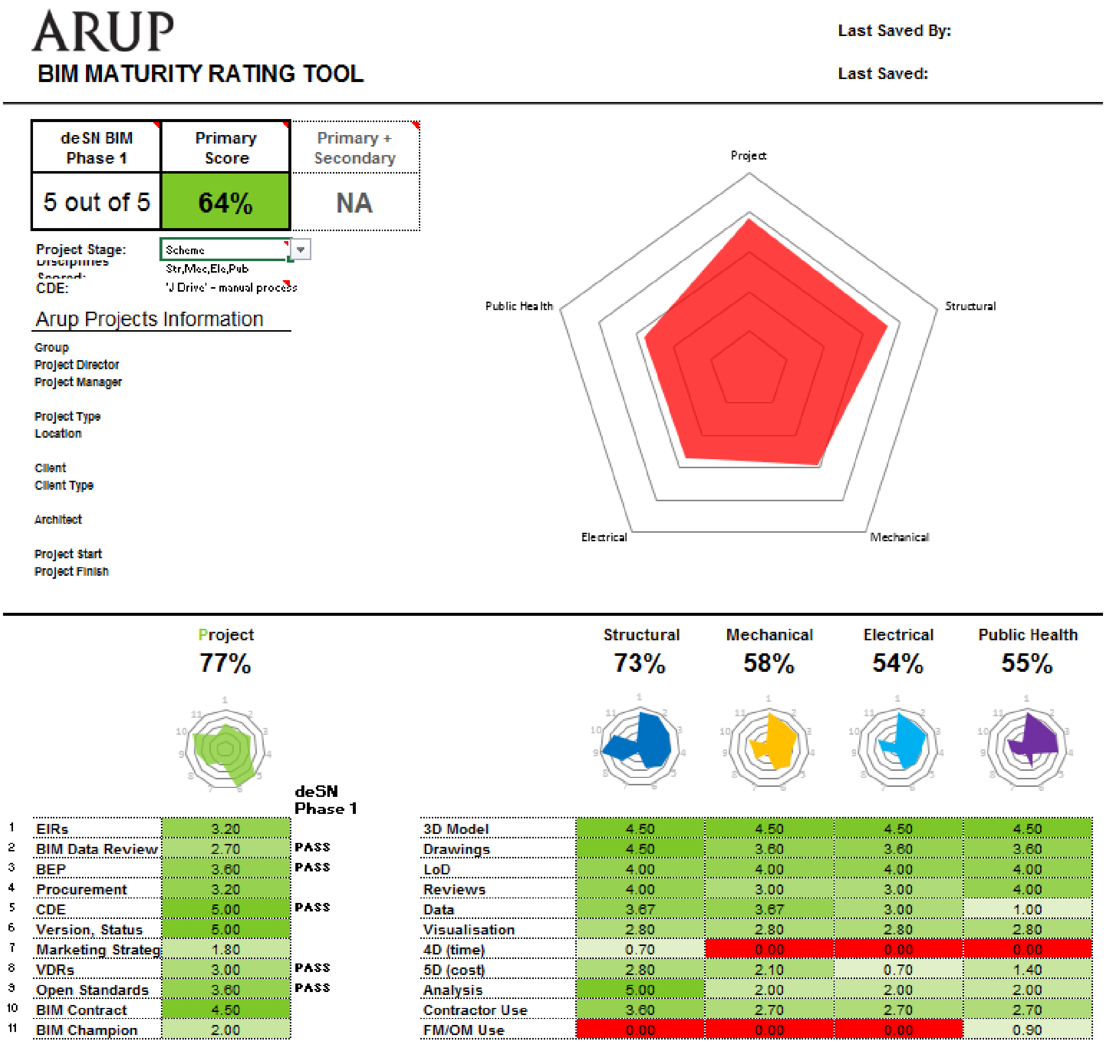


Figure 23 Reporting results in BIM-MM (Arup, 2014)

Since AMs cover a wide-range of different measures, with some including over seventy measures, it is crucial to present the results in a clear engaging way which meaningfully communicate the outcomes of the assessment. It is this stage that 'story' of the AM must be reported in an informative and coherent manner (Cole, 1998). Having discussed the communications of results of BIM-AMs, the following documents the use of levels of maturity which have been widely applied in different AMs to layer BIM implementation processes.

5.6 BIM Maturity Levels

Maturity levels have been implemented in different disciplines including project management, construction enterprises and environmental buildings. They are defined as evolutionary stages towards reaching particular process milestones within an organisation a team or a project. Higher maturity levels tend to build on the requirements of the lower ones (De Bruin et al., 2005), and their progression to higher levels reflects better process control, greater predictability and improved effectiveness (Succar, 2010a). The numbers of maturity levels applied in BIM-AMs showed consistency of either five or six levels, similar to other observed disciplines (Chapter 2).

Most existing BIM-AMs have used BIM maturity levels but in two different ways. Firstly, in some of the AMs, maturity levels have been implemented as a way of communicating final results. Namely, following the completion of the assessment, an overall score is reported and then allocated to a specific maturity level. This method of classification is beneficial for the AEC industry to better understand the meaning of the assessment outcomes. For instance, in the BIM Proficiency Matrix, after completing the assessment, an overall score is obtained and then directed to one out of five maturity levels (Indiana University Architect's Office, 2009a), as illustrated in Table 21. Similar approaches can be also found in other models including the NBIMS-CMM and the VDC Scorecard (Figure 24).

Table 21 The use of levels of maturity as a way to understand overall score in the BIM Proficiency Matrix (Indiana University Architect's Office, 2009a)

BIM Maturity Category	Points Achieved	BIM Maturity Score	BIM Standard		
A - Physical Accuracy of Model	1	19	BIM Score Between 0-12	=	Working Towards BIM
B- IPD Methodology	2		BIM Score Between 13-18	=	Certified BIM
C - Calculation Mentality	4				
D - Location Awareness	2		BIM Score Between 19-24	=	Silver
E - Content Creation	3				
F - Construction Data	3		BIM Score Between 25-28	=	Gold
G - As-Built Modeling	0		BIM Score Between 29-32	=	Ideal
H- FM Data Richness	4				

Figure 24 Five levels of maturity applied in the VDC Scorecard (Kam et al., 2013b)

Secondly, some of the AMs use maturity levels as multiple-option answers to their questions. This can be accompanied with a brief description explained in the matrix for each maturity level. What is crucial to address here is to design these levels to be distinct, well-defined and to have logical progression through the increasing stages. Maturity levels tend to start usually with 0 non-existent (sometimes called initial or minimum BIM) which reflects the absence or the limited use of the evaluated measure and they continue to increase to reach highest levels of maturity where the measure is most optimised and advanced (Table 22). By using these levels, professionals can identify their current implementation status and identify future desired directions. Instances of this approach can be found in several models including the BIM Excellence Individual Assessment, the BIM Maturity Matrix and the BIM Maturity Measure where each measure has multiple possible maturity levels. For instance, in the Organisational BIM assessment profile, when evaluating 'BIM Champion', participants have to choose one out of five maturity levels:

- 0 Non-Existent: No BIM Champion
- 1 Initial: BIM Champion identified but limited time committed to BIM initiative
- 2 Managed: BIM Champion with adequate time commitment
- 3 Defined: Multiple BIM Champions with each working Group
- 4 Quantitatively Managed: Executive Level BIM Support Champion with limited time commitment
- 5 Optimising: Executive-level BIM Champion working closely with working group champion

As discussed in Chapter 3, the broader AMs in different disciplines have shaped the BIM-AMs in different ways including the use of maturity levels. The building environmental AM, LEED applies five levels of maturity (Not Certified, Certified, Silver, Gold or Platinum). These levels were adopted by the first BIM-AM, the NBIMS-CMM. A number of years later, they have been also implemented in the BIM Proficiency Matrix. Furthermore, the maturity levels applied in the BIM Maturity Matrix have been chosen through the investigation of different maturity models across different industries (Succar, 2010b). they have been then adopted later by the Organisational BIM Assessment Profile and more recently by the BIM Maturity Measure (Arup, 2014). BIM-AMs have been shaped and informed by AMs in different disciplines but they have been also influenced internally by each other. However, it is crucial to note that maturity levels across the diverse BIM-AMs are not comparable since they reflect different content and employ different scoring systems and weighting criteria.

Table 22 Comparison of BIM maturity levels within different tools

BIM-AM	**BIM Maturity Levels**					
NBIMS-CMM	Minimum BIM (40-59.9)	Certified (60-69.9)	Silver (70-79.9)	Gold (80-89.9)	Platinum (90-100)	
BIM Excellence individual assessments	0 None	1 Basic	2 Intermediate	3 Advanced	4 Expert	
BIM Proficiency Matrix	Working towards BIM (0-12)	Certified BIM (13-18)	Silver (19-24)	Gold (25-28)	Ideal (29-32)	
BIM Maturity Matrix	a Initial/Ad-hoc	b Defined	c Managed	d Integrated	e Optimised	
Organisational BIM assessment profile	0 Non-Existent	1 Initial	2 Managed	3 Defined	4 Quantitatively Managed	5 Optimised
VDC Scorecard/bimSCORE	Conventional Practice (0-25%)	Typical Practice (25-50%)	Advanced Practice (50-70%)	Best Practice (70-85%)	Innovative Practice (85-100%)	
The Owner's BIMCAT	Level 0 Non-Existent (0-200)	Level 1 Initialised (200-400)	Level 2 Managed (400-600)	Level 3 Defined (600-800)	Level 4 Quantitatively Managed (800-1000)	Level 5 Optimising (1000-1200)
BIM-MM	0 Non-Existent	1 Initial	2 Managed	3 Defined	4 Measured	5 Optimising

5.7 The implementation of BIM-AMs

Despite the continuous development of BIM-AMs, there has been until recently little evaluation of the implementation of many BIM-AMs in practice. This implementation is of vital importance to shift the field of BIM-AMs from its theoretical approach into an effective and practical context, a challenge documented by Neely et al. (2000):

> The process of designing a measurement system is intellectually challenging, fulfilling and immensely valuable to those managers who participate fully in it….[However,] the real challenges for managers come once they have developed their robust measurement system, for then they must implement the measures.

As suggested in the above quote, one of the critical challenges of AMs is examining them in practice; a problem which has been continuously reported in the BIM domain (Giel, 2013; Kam et al., 2013b). Past research has found no available data on applying nine of the current AMs in practice. The Organisational BIM Assessment Profile (CIC, 2013) and the BIM Proficiency Matrix (Indiana University Architect's Office, 2009a), for instance, have contributed remarkably to the field of BIM-AMs but no existing publications address their examination in practice.

Nevertheless, a number of exceptions can be found in the literature of BIM measurement as presented in Table 23. Some of these studies, however, provide only a couple of case studies as in the Owner's BIMCAT and the Goal-driven method for evaluation of BIM project. Saying that, three remarkable studies provide substantial dataset on the application of BIM-AMs in practice. They will be introduced in the following.

Table 23 Implementation of BIM-AMs in practice

	BIM-AM	Number of case study projects	Reference
1	NBIMS-CMM	11	(McCuen et al., 2012)
5	BIM Quickscan	130	(Berlo et al., 2012)
10	VDC Scorecard/bimSCORE	130	(Kam, 2015)
11	Owner's BIMCAT	2	(Giel, 2013)
12	BIM-MM	213	(Arup, 2014)
13	Goal-driven method for evaluation of BIM project	2	(Lee & Won, 2014)

The first study applies BIM-MM to 213 projects which the author's research team published in association with Arup (Azzouz, Copping, et al., 2016), see Appendix B for the full paper co-authored by the Arup's BIM Development Manager; Andrew Duncan.

To date, the study offers the highest number of case study projects in the field of BIM-AMs. It provides a strong practical relevance to the research field. This academia-industry collaboration shows how through the use of Arup's BIM-MM it is possible to draw an overarching view of BIM's levels of maturity across projects. Therefore, the contribution of the study does not only lie in offering substantial datasets of BIM measurement, but more importantly to shed light on how BIM is being used in practice. The study starts with a comprehensive illustration of BIM implementation in Arup against five levels of maturity across the eleven measures included in the BIM-MM. Through this illustration, areas of strengths and weaknesses can be identified which help businesses to improve their performance and set future targets.

The study then directs a particular focus on the BIM Champion, one of the evaluated measures, since there is only a few sources in the literature on their rules and impact in the BIM implementation process. It is observed that overall scores of all projects increase gradually when BIM Champions have greater levels of engagement in the BIM implementation process, as illustrated in Figure 25. This shows how essential it is to have BIM Champions to guide the teams and push BIM utilisation in projects.

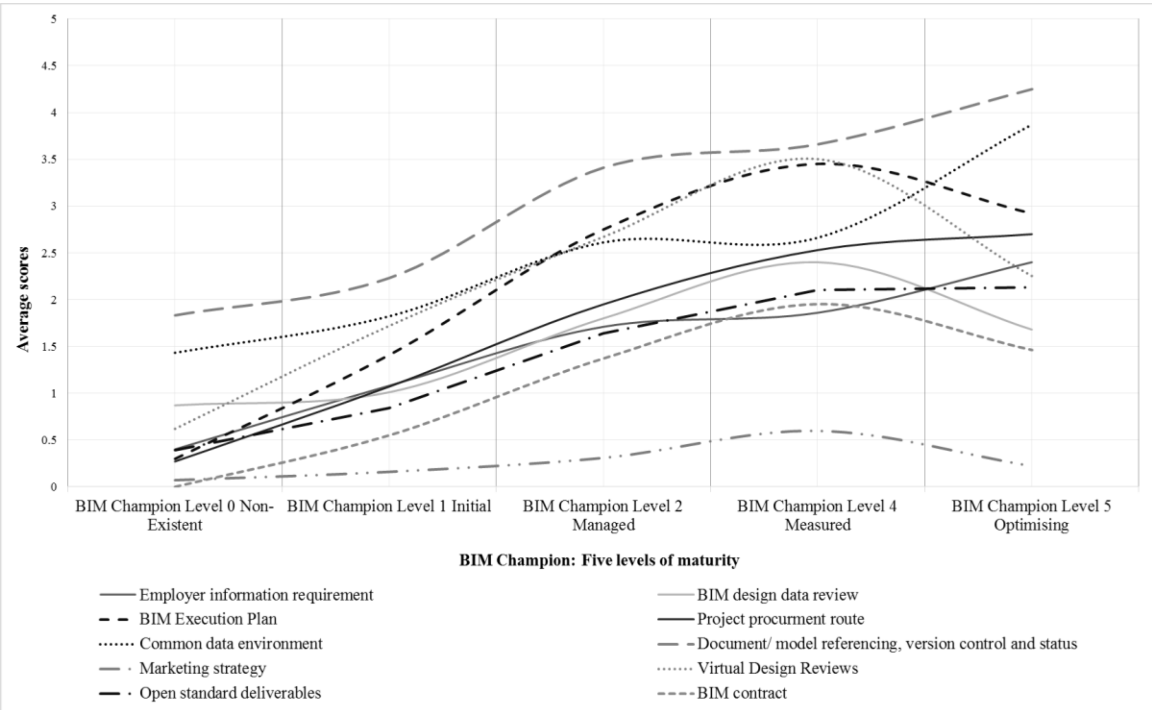


Figure 25 The impact of the BIM Champion on the rest of the measures

The second study is reported by Kam (2015) who captures the implementation of the VDC Scorecard to 130 case study projects across thirteen countries. This examination allowed CIFE researchers to evaluate the AEC projects and understand industry trends such as the average scores of multiple projects. It also helped them to address critical issues of their AM including validation, successes, shortcomings and future directions (Kam et al., 2013a).

This implementation provides a better understanding of how professionals can investigate their maturity levels in the Scorecard's four main evaluated areas i.e. planning, adoption, technology and performance as seen in Figure 26. The figure shows that the overall scores (of all 130 projects) of the four main areas is the highest in Technology, which reflect how the industry is more advanced in the technology side of BIM when compared to other areas such as performance and adoption.

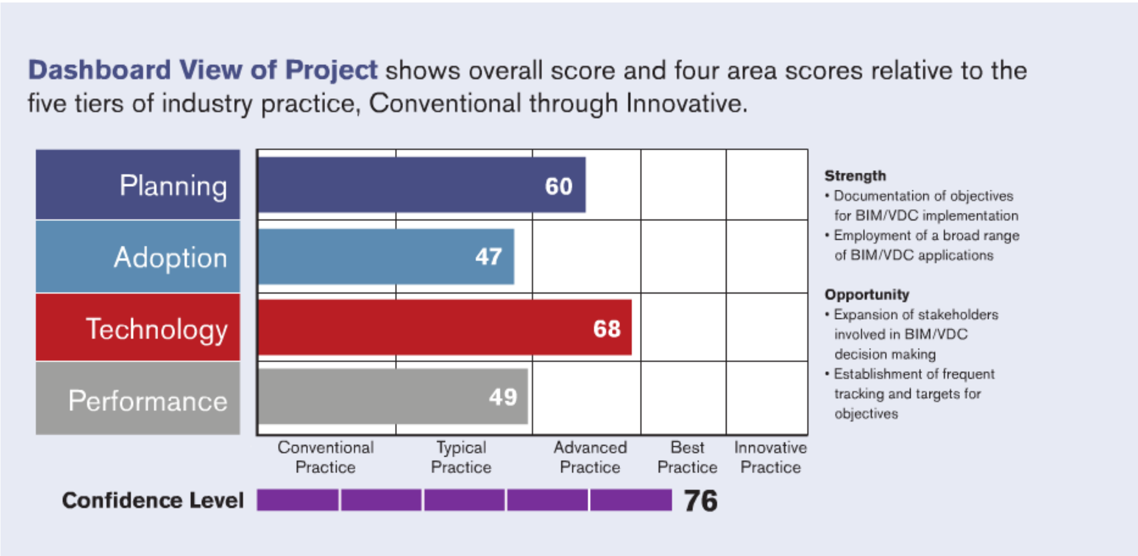


Figure 26 The scores obtained in each of the four measured area

The Scorecard can also be helpful in assessing the same project at different periods of its lifecycle. The application of the VDC Scorecard at early stages of the project might assist the owners and BIM implementation teams and managers to establish their objectives and identify the desired level of proficiency and skill sets. As the projects progress, continuous evaluation (a weekly-basis, Kam suggests) might help professionals in tracking performance over time, record improvements and distinguish limitations when they occur, as presented in Figure 27.

Furthermore, the implementation of the scorecard enables comparisons between different projects, disciplines and regions. Figure 28 shows a comparison of three different projects which includes their overall average score and the differences of scores across the four main areas of the VDC Scorecard.

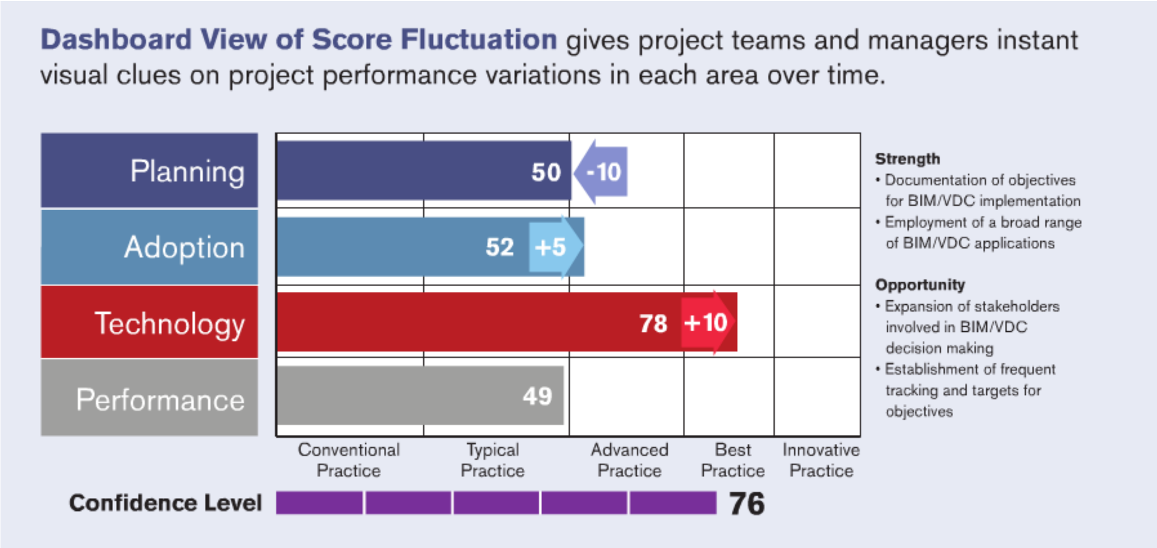


Figure 27 An illustration of how a project score can change at different periods of its life-cycle

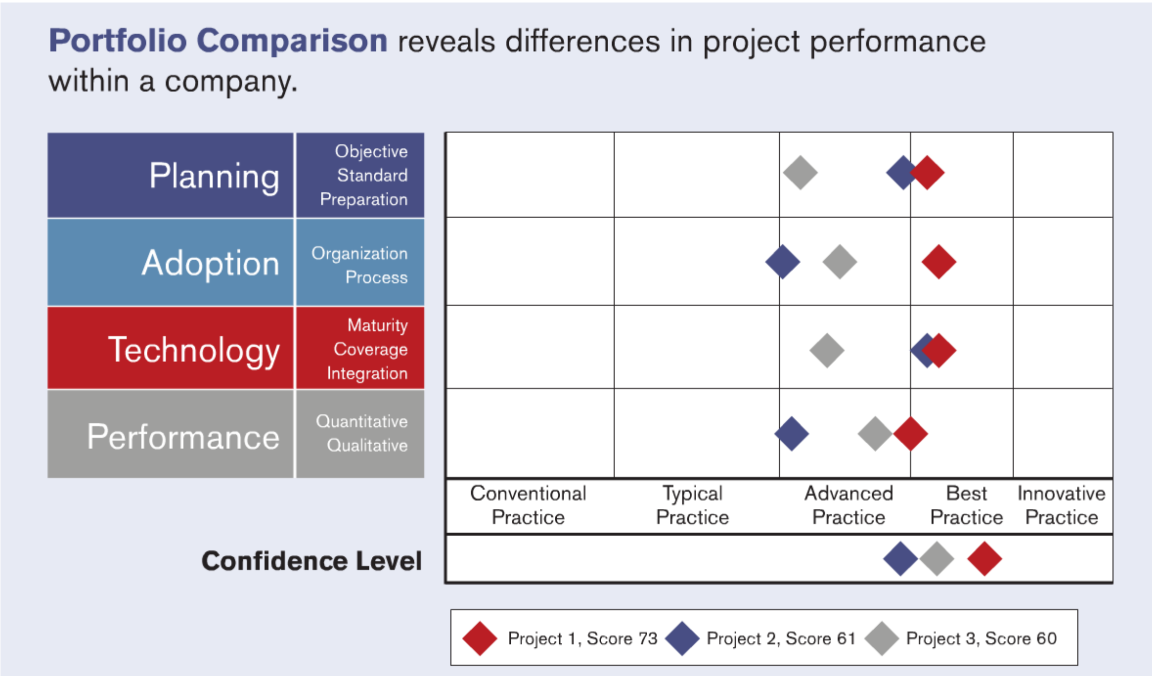


Figure 28 An example shows the use of VDC Scorecard to compare projects across the market

The third study that documents the implementation of a BIM-AM in practice is carried out by Berlo et al. (2012) who report the implementation of BIM Quickscan to 130 projects in order to explore the average levels of BIM in the Netherlands. This has helped them to identify a series of trends including the average BIM level in each of the four measured categories (Figure 29), and the average BIM level per sector (Figure 30). By doing so, they identify that the highest levels of maturity are to be found in the 'Mentality and Culture' category whilst the lowest is in 'Tools and Applications'. The scans have also helped to identify the leading sector of BIM implementation. As seen in Figure 30, Construction and MEP engineers have the highest scores in all categories across the different disciplines.

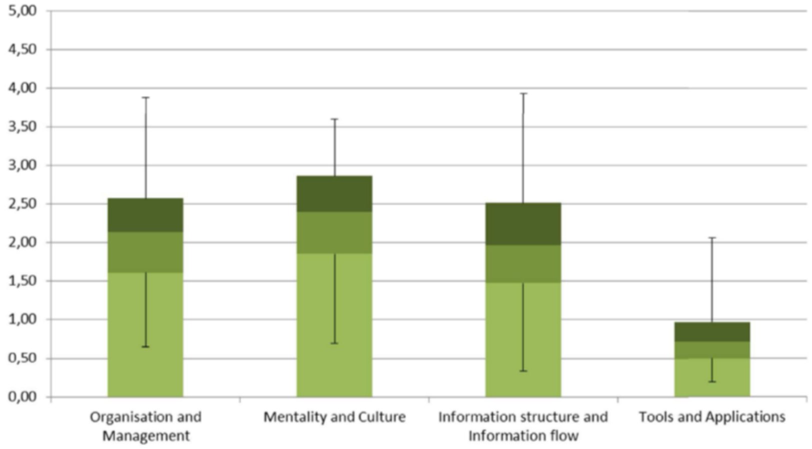


Figure 29 Average BIM level per category across 130 'scans' by certified consultants

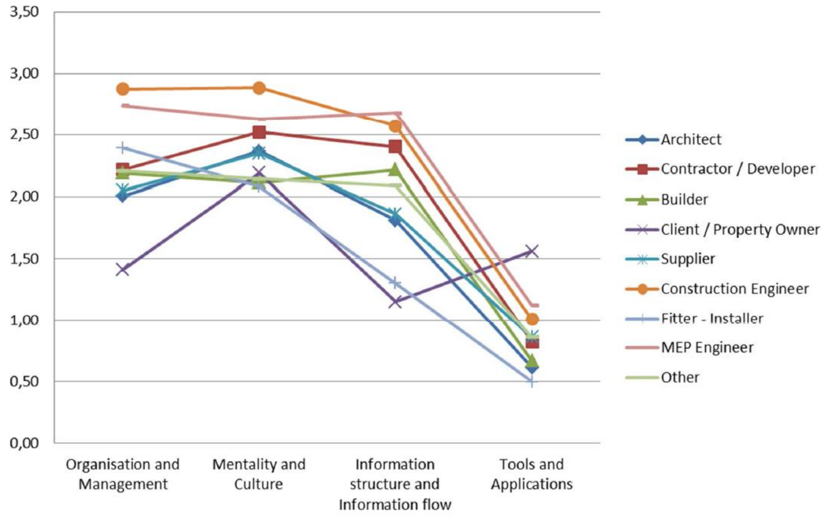


Figure 30 BIM level per category across different teams across 130 'scans' certified consultants

The application of case study projects, as in the three reported instances, is essential to encourage holistic and in-depth investigations of BIM-AMs. For researchers, it helps identifying areas of opportunities and challenges to improve the coexisting AMs. For policy-makers, it presents the overall levels of maturity of BIM implementation amongst the AEC industry. For professional firms, it highlights their strengths and weaknesses at the time the case studies were carried out.

5.8 The development of BIM-AMs

This section concentrates on the design process of BIM-AMs which has recently been the subject of significant research (Chen et al., 2012; Dib et al., 2012; Shin et al., 2015a, 2015b). Designing a BIM-AM is a complex process and one of the main critical questions that needs to be addressed in this process is how to select the appropriate measures. To answer this question, researchers have derived their measures using different approaches and diverse research methods.

Many past BIM-AMs have been released without explaining the development process of these models. This is widely seen in the industry developed models (CPI, 2011; VICO, 2011). The first developed AM, the NBIMS-CMM has been presented extensively in three reports to date, but none of them addresses its system design (NIBS, 2007, 2012, 2015). Similarly, the most recent AM, the BIM Level 2 BRE certification, has been launched but neither the measures included nor the development process of the model have been documented (BRE, 2015b). Even some of the research-based models have not addressed the design process of AMs including the BIM Proficiency Matrix and the Organisational BIM Assessment Profile.

In contrast, several researchers have discussed the process of deciding what to measure. Sebastian and Berlo (2010), for example, argued that the development of their tool, the BIM Quick Scan, consisted of three main steps. The first included desk research and investigation of current BIM measurement literature. To do so, they interviewed professionals in the AEC industry to decide the main areas of assessment. In addition, they critically reviewed existing BIM literature to learn lessons from past AMs. The second step focused on setting-up the assessment criteria and categorising them into 'hard' and 'soft' quantitative and qualitative aspects. To decide which measures to include, five rounds of three experts (who were involved in the first step) were carried out. The third step concerned the verification and the validation of the assessment aspects developed in the previous step. The verification was based on the critical comments from 15 expert panels which was repeated twice. The validation of the model was built on applying it in two pilot cases.

Giel (2013) proposes a more detailed process for designing the Owner's BIMCAT which consists of five stages, illustrated in Figure 31. The design process is similar to Sebastian and Berlo's approach, in that it starts with exploration of literature review and ends with the validating the model. It is also similar in the way that expert panel (including 21 BIM experts) is integrated to define the selected measures. The difference between the two proposed processes, however, is particularly linked to the way measures are initially proposed. In the BIM Quick Scan, measures in the first step are derived from literature and interviews, whilst they are only taken from comprehensive literature before being distributed in a survey by Giel. Unlike, Sebastian and Berlo, Giel did not only review and criticise past AMs, but also compared them to identify their synthesis. Another difference between the two models is reported in the prioritisation stage. The final 66 measures have been prioritised using the Delphi Method, a survey research method that aims to organise group discussion and opinion (Goodman, 1987). This included three rounds (Giel & Issa, 2014):

- Round 1: participants were required to express their perceptions of 68 initial BIM measures extracted from the reviewed literature. Measures chosen by less than half of the participants were removed (six measures), whilst four additional measures were added suggested by participants
- Round 2: participants were required to rate the importance of each measure
- Round 3: participants to reconsider their ratings with a final 66 evaluated measures

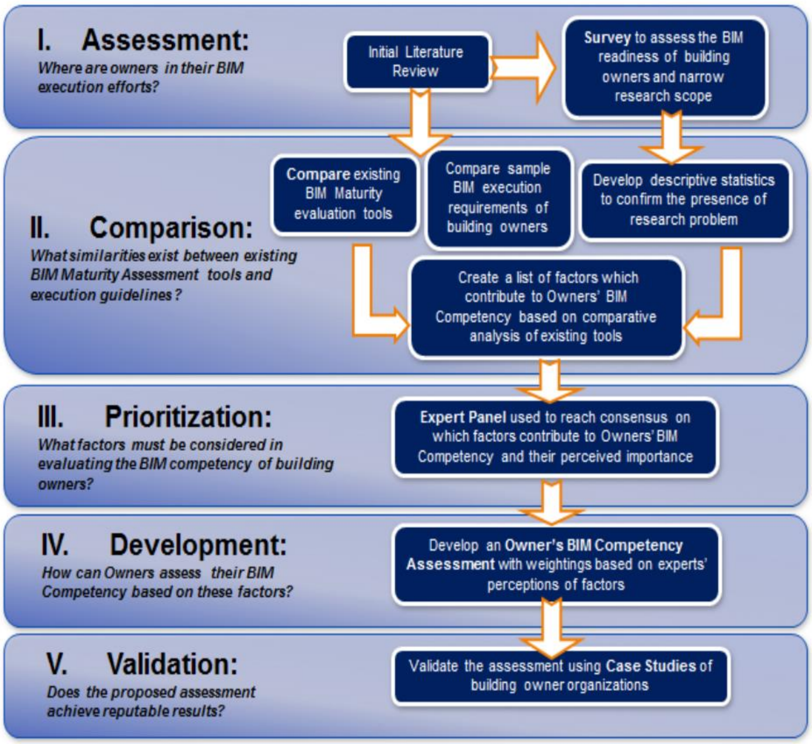


Figure 31 Proposed research methodology to assess BIM (Giel, 2013)

Gao (2011), the developer of the Characterisation Framework (discussed in Section 3.6.3), follows a slightly different approach. In her thesis, she chooses pre-existing multiple case studies combined with grounded theory as the main research methods rather than survey or experiment methods as in the last two stances. In the development process of the Characterisation Framework, Gao applies three phases of case studies which covers a total of 40 projects chosen from the reviewed literature. The three phases are:

- Phase 1: Framework 1 investigates 21 case projects to derive BIM factors which included 3 categories, 13 factors and 38 measures.
- Phase 2: Following the revision of Framework 1, Framework 2 explores additional 11 case study projects and adds the newly found measures, this includes 3 categories, 13 factors and 63 measures based on 11 case studies.

- Phase 3: Final framework contains 3 categories, 14 factors and 74 measures and tested 8 projects meaning an overall 40 projects.

Each of the three phases includes three major research tasks. Figure 32 summarises the research process undertaken in each stage and shows how the framework of each phase is refined building on observations from previous stages.

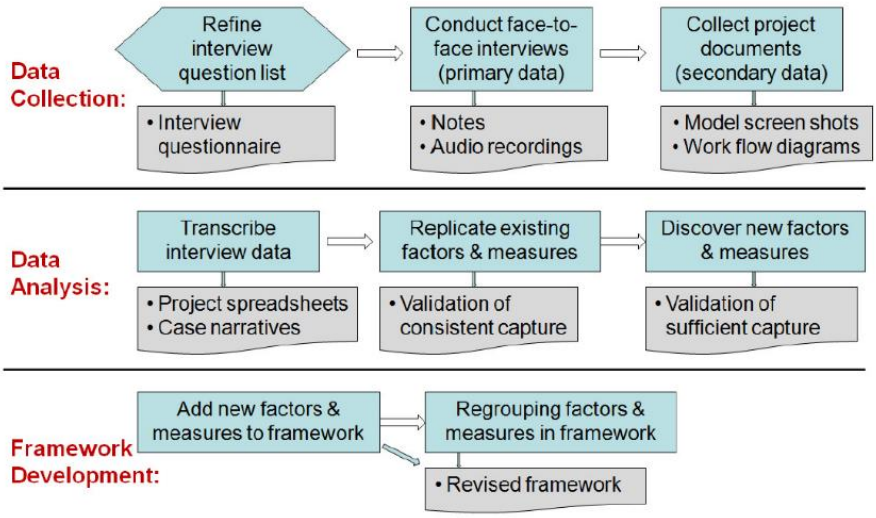


Figure 32 Completed case studies when developing the Characterisation Framework

Another example can be found in the BIM Maturity Matrix. In his early writings, Succar did not explicitly explain the design process of the model and how the measures were selected, which are critical issues in the field of performance measurement. The matrix, however, is built on a combination of knowledge infrastructure and research methodologies , explained in detail in Succar's PhD thesis (Succar, 2013). The matrix combines a set of concepts: the BIM Capability Stages and BIM. In an email exchange, Succar added that these stages and sets were developed based on literature reviews and experimental knowledge. They were then examined through focus groups across three countries, i.e. UK, U.S. and Hong Kong.

Observations of the BIM literature indicate that there have been little details directed towards the design process of AMs. Indeed, only the four above studies highlight the process of designing their assessments. Each applies a different approach and therefore has its own advantages and disadvantages. Take, for instance the Owner's BIMCAT. In the development of this tool, the Delphi Method was applied. The method is advantageous since it requires experts who have experience in the field (Franklin & Hart, 2007) but it also reflects the experts' opinion and not the "indisputable fact" (Powell, 2003).

5.9 Discussion and conclusion

There have been many influences and forces impacting upon the development of BIM-AMs these are both external, namely, AMs in different research fields, as explained in Chapter 2, and internal in which BIM-AMs build upon each other and inform later models, discussed in Chapter 3. The synthesis of the literature of these two forces is concerned with the comparative analysis of the assessment's general characterisations, which have been the subjects of Chapter 5. From these conclusions, it is hoped that Figure 33 would sharpen the focus on the integration between these two forces and emphasise the critical issues that should be addressed in regard to understanding the evolution of BIM-AMs including their design process, content and reporting results.

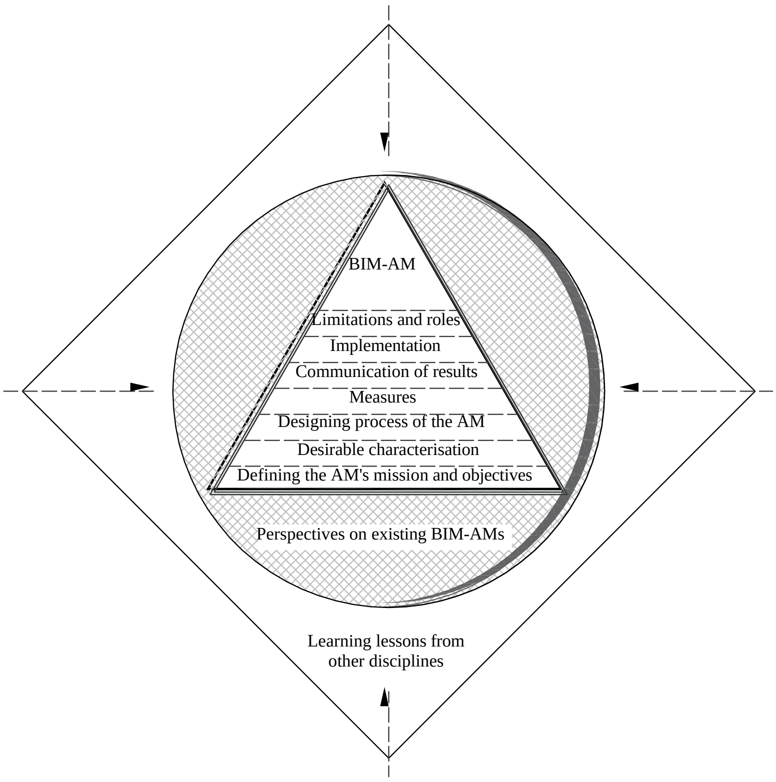


Figure 33 Influences that impact the evolution of BIM-AMs

As discussed in Chapter 3, one of the main limitations of most emerging academic and industry-based contributions on BIM measurement is the lack of a comprehensive comparison which brings together the broad research body of the BIM-AMs as a coherent whole. This is crucial since comparison is a 'fundamental tool of analysis, it sharpens our power of description and plays a central-role in concept formation by bringing into focus suggestive similarities and contrasts among cases' (Collier, 1993). Currently, there are only a couple of research studies that critically compare the key distinguishing characterisations of BIM-AMs.

Chapter 5 contributes to this little researched field by comprehensively exploring the relationship between all the coexisting AMs. This overarching comparison enables valuable insights in widening the rigour and the scope of BIM-AMs. In order to summarise the emerging literature of BIM-AMs, Figure 34 shows their gradual development since 2007. The figure explores the 16 existing models and presents their key characterisations. This includes the number of areas and measures of each AM, their origin, the assessment focus and whether they are research or industry-based.

This assessment of the BIM measurement literature maps the current landscape of BIM-AMs and can be used by professionals, researchers and policy makers working on the evaluating BIM levels of maturity. It is an important account of the AMs that have individually and collectively shaped the research field of BIM performance measurement in particular and BIM from wider perspective. It builds on detailed analysis of the literature and should be updated to address emerging models. It is valuable to collectively explore the history of the AMs' research field which will inform and engender the future directions of BIM performance measurement.

However, the discussion of AMs spans beyond comparing their major properties. What is needed to extend the understanding of practical and technical features of assessments is to apply them in practice. Initial testing of three AMs in practice will be carried out in Chapter 6, whilst more detailed examination is documented in Chapter 7.

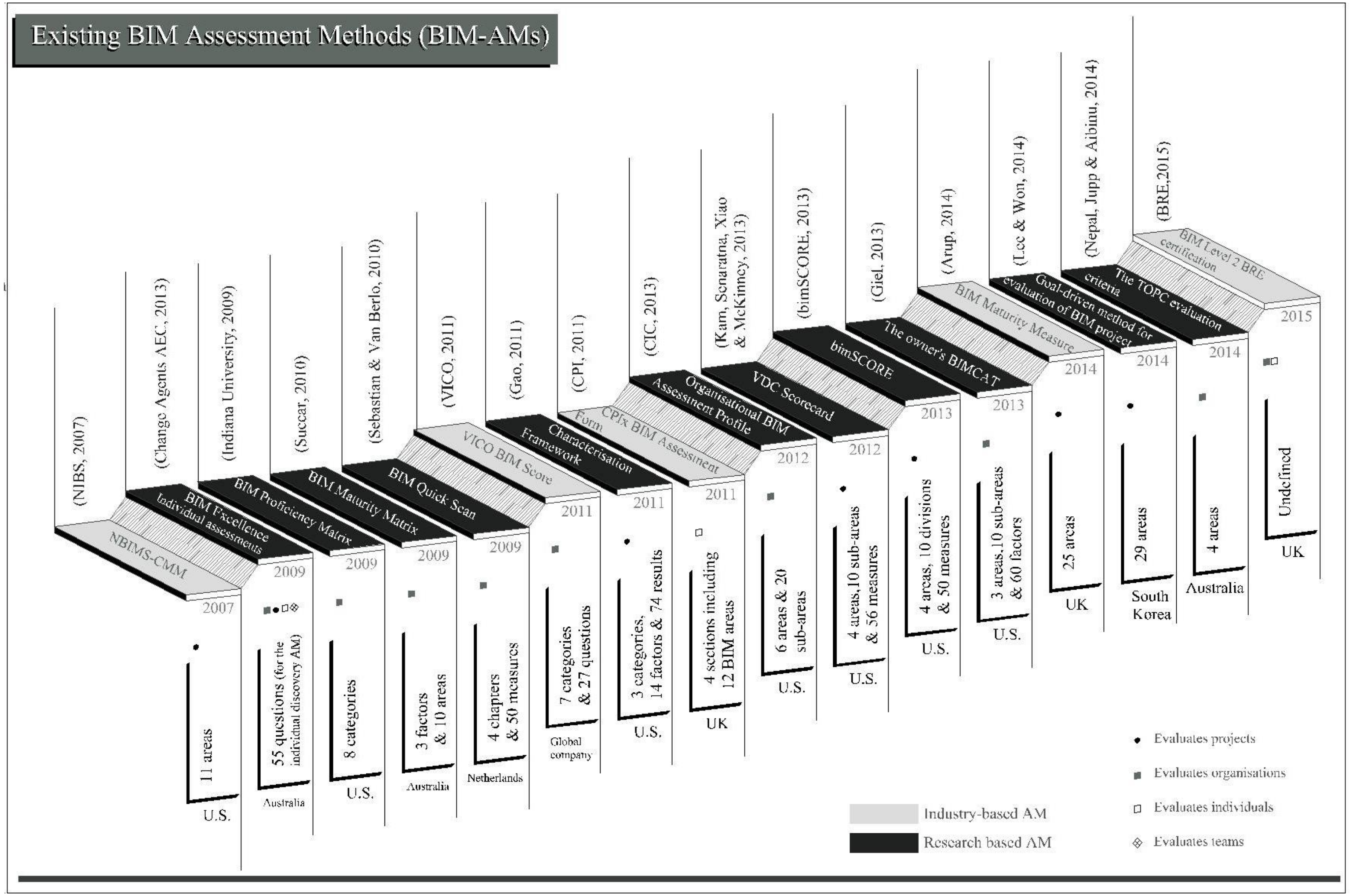
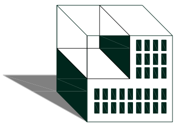
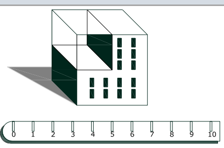
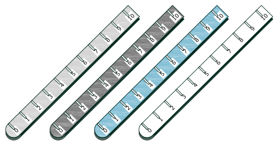
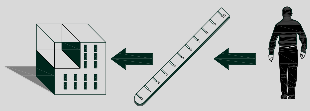
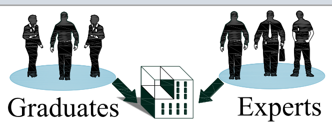
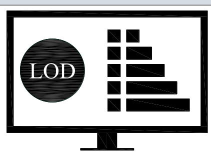


Figure 34 The evolution of BIM-AMs

6 Pilot study: initial testing approach of current BIM-AMs

In Chapter 5, a significant body of theoretical research has been provided to compare the core features of AMs. However, throughout this thesis, it has been observed that there is a lack of implementation of AMs in practice, which is crucial to investigate AMs' practicality and validity. To address this gap, described in Section 5.7, this chapter details initial testing of two AMs in the UK's AEC industry, prior to undertaking more overarching testing in Chapter 7.

1: Introduction	**2: PMSs**	**3: BIM-AMs**
		
Main questions included: What is BIM? What is the need for BIM-AMs?	Includes: - Brief history of the broad PMSs, their definitions - PMSs roles and barriers - Sample of PMSs	- Explains the wide range of BIM-AMs, their evolution, opportunities and challenges - Investigates how BIM-AMs have been informed by the broader PMSs
4: Research methodology	**5: Perspectives on BIM-AMs**	**6: Pilot Testing**
		
Introducing the chosen research methods including questionnaire, interview and the implementation of multiple AMs in practice	- Critical analysis of the BIM-AM, their similarities and differences - This includes the design process, the complexity and the range of measures	Initial testing of individual and multiple AMs in practice in association with a number of practices
7: Comprehensive testing	**8: Automated BIM-AM**	**9: Conclusions**
		
In association with Arup, applying three AMs to the same project and completed by six participants who have different BIM experience i.e. experts and graduates	Includes: - The need for automated AMs - The implementations of BIM-AM in practice	Current perspectives and future directions of BIM-AMs

6.1 Introduction

Two of the current AMs are applied in the AEC industry to explore their practicality. These AMs are the National BIM Standard Capability Maturity Model (NBIMS-CMM) Version 2 (NIBS, 2012), which was the most updated version of the AM at the time of the testing, and the Virtual Design and Construction (VDC) Scorecard Version 1.3 (CIFE, 2013). There are a number of similarities and differences between the two applied AMs. Both evaluate "projects" and include multiple maturity levels for each measure. However, they differ in some important respects. NBIMS-CMM is a simplified, brief, non-research based tool. Conversely the VCD Scorecard is a detailed, comprehensive and research-based AM. Table 24 provides a brief comparison between the two AMs.

Table 24 Comparison between NBIMS-CMM and VDC Scorecard

BIM-AMs	**NBIMS-CMM**	**VDC Scorecard**
Country of origin	U.S.	U.S.
Developer	The National Institute of Building Sciences (NIBS)	Researchers at the Centre for Integrated Facility Engineering (CIFE), Stanford University
Availability	Available freely on-line	Available freely on-line
Research vs Non-Research	*Industry* based AM	*Research* based AM
Year of release	2007	2009
Evaluation Level	Evaluates projects	Evaluates projects
Number of measures	11 areas of interest	4 areas, 10 sub-areas and 56 measures
Range of measures	*Simplified* and focused	*Detailed* and comprehensive
Website	http://www.nationalbimstandard.org/	https://vdcscorecard.stanford.edu/content/point-departure
Number of versions	1 Version, 3 updates (2007, 2012, 2015)	2 Versions, the Full and the Express versions
Documentation	Three updated reports that document the development of the NBIMS-CMM	At least five papers that introduce the VDC Scorecard and apply it in practice

The reason behind selecting these two AMs for further study is that the emphasis of this research is on evaluating 'projects', and not 'organisations', 'teams' or 'individuals'. The choice of evaluating 'projects' is based on the need to understand how BIM is being implemented in practice and how companies can improve their BIM's levels of maturity through the use of these AMs. This limited the options to five AMs that evaluate projects out of the 16 existing AMs. Three of them are applied in this thesis, two in the initial testing in Chapter 6 and three of them in Chapter 7 (including the Arup's BIM Maturity Measure). The selected BIM-AMs are the only well documented tools available to evaluate BIM level of maturity of 'projects'. The Characterisation Framework (Gao, 2011), for instance, is documented thoroughly in regards to its design process and the measures included, as discussed in Section 3.6.3, however, the AM itself is not available for use.

The initial testing approach of current BIM-AMs in this chapter includes three different phases, each has its own focus. These phases are:

- Phase 1: applying one BIM-AM to multiple projects (score comparison)
- Phase 2: two different participants applying one BIM-AM to a single project (user comparison)
- Phase 3: the same participant applying two BIM-AMs to the same project (model comparison)

Together, these three phases cover ten Case Study Projects (CSPs); seven in Phase 1, one in Phase 2 and two in Phase 3. The tested projects were selected from companies who apply BIM in their practice. Companies were invited to participate in this study through on-line posts in BIM groups on LinkedIn, or by emails to specific contacts in 2014 and 2015. Once companies confirmed their availability, they were then required to specify a number of BIM projects, and to apply one or two of the BIM-AMs to them. Prior to testing, participants were introduced to the AM(s), since most had no previous knowledge of BIM-AMs. Each AM took between 20 minutes to an hour to complete.

6.2 Phase 1: applying one BIM-AM to multiple projects (score comparison)

In Phase 1, the NBIMS-CMM is applied to seven CSPs in association with five UK-based AEC companies (some companies offered two CSPs, Table 25). This implementation is valuable not only to test the AM itself in practice but also to understand the way BIM is being used and or misused in a sample of the UK's AEC industry.

Tested projects needed to be kept confidential and they are therefore referred to by letters ranging from Project A to G. As explained in Chapter 4, the NBIMS-CMM consists of eleven measures that reflect the use of BIM in projects. To evaluate each project, participants specify the levels of maturity of these measures. Each measure has ten possible maturity levels ranging from level 1 to level 10, with level 10 being the most advanced. Measures are differently weighted across the assessment to reach a maximum overall score of 100 points. The weights of each measure vary and was decided by a vote of the NBIMS executive board (NIBS, 2007). The overall score is then allocated to a particular maturity level i.e. Not Certified, Minimum BIM, Certified, Silver, Gold, or Platinum.

6.2.1 Findings:

The average overall score of all seven CSPs is Minimum BIM 56.8 points, which is a weighted average of the eleven measures (Table 25). None of the projects score below 40 points, which, according to the NIBS, means that all these CSPs are implementing BIM. The lowest reported score is 51 points in Project F whilst the greatest is 66.6 points in Project D, making it the only 'Certified' project across the examined case studies, all the rest of the projects are allocated to Minimum BIM level of maturity.

Areas of similarities and differences between all projects are illustrated in Table 25. It provides the scores of all measures across projects in addition to the total score of each project as seen in the 'Overall Score' row. This clear illustration of numerical findings enables investigation of relationships and patterns between multiple CSPs. The average score for each *measure* across the seven CSPs is calculated and presented in the last column of Table 25. The lowest average scoring measure can be found in 'life-cycle views' with only 3 points. The highest, however, is reported in 'Graphical Information' (this will be discussed later in section 6.2.2). The results show significant differences in scores across the 11 measures (highest score of each measure across projects is highlighted in grey in the table, whilst lowest score of each measure is in bold). One of the most noticeable differences can be found in the 'Change Management' area, where 2.7 points are recorded in Project B compared to 9.0 points in Project E. In contrast, scores across the seven projects prove to be roughly similar in two measures; 'Data Richness' and 'Graphical Information'. Variations across the seven projects were expected, because every organisation prioritises different areas of BIM. Some companies, for instance, focus on the 'Interoperability/IFC Support' (Project A and D, 7.7 points), whilst in other companies more attention is given to the 'Delivery Method' area (Project F, 8.3 points).

Table 25 CMM score for seven case study projects

Measure/Project	Company 1	Company 2	Company 2	Company 3	Company 3	Company 4	Company 5	**Average Score**
	Project A	**Project B**	**Project C**	**Project D**	**Project E**	**Project F**	**Project G**	
Data Richness	5	5.9	6.7	5.9	5	**4.2**	5.9	5.5
Life-cycle Views	2.5	3.4	3.4	4.2	2.5	**1.7**	3.4	**3**
Change Management	4.5	**2.7**	**2.7**	7.2	9	4.5	3.6	5.9
Roles or Disciplines	5.4	5.4	3.6	**2.7**	4.5	5.4	5.4	4.6
Business Process	**2.7**	3.6	3.6	6.4	**2.7**	**2.7**	**2.7**	3.4
Timeliness/Response	3.6	3.6	4.6	7.3	**2.7**	8.2	4.6	4.9
Delivery Method	4.6	5.5	4.6	6.4	**3.7**	8.3	4.6	5.3
Graphical Information	8.4	7.4	7.4	**6.5**	7.4	8.4	7.4	7.5
Spatial Capability	9.4	7.5	6.6	4.7	**2.8**	**2.8**	**2.8**	5.6
Information Accuracy	**4.8**	7.6	8.6	7.6	8.6	1.9	6.7	6.5
Interoperability/IFC Support	7.7	5.8	5.8	7.7	3.8	**2.9**	5.8	5.6
Overall Score	*58.6*	*58.5*	*57.5*	*66.6*	*52.9*	*51*	*52.8*	*56.8*
BIM Level of Maturity	Min-BIM	Min- BIM	Min- BIM	Certified	Min- BIM	Min- BIM	Min- BIM	Min-BIM

6.2.2 Graphical Information

To obtain a further understanding of the different scores across the seven projects, one of the eleven measures is selected for detailed analysis in this section. The selected measure is 'Graphical Information', which has the highest average score across the eleven measures (7.5 points as highlighted in grey in Table 25). In addition to the description of maturity levels, the NIBS provides description to each measure and in Graphical Information the description is (NIBS, 2007):

> "The advent of graphics helps paint a clearer picture for all involved. As standards are applied then information can begin to flow as the provider and receiver must have the same standards in place. As 3D images come into play more consumers of the information will have a common view and a higher level of understanding will occur. As time and cost are added then the interfaces can be expanded significantly."

Graphical Information, as with all the rest of the measures, is allocated to one of ten evolutionary levels of maturity from which participants have to select one from. The NIBS provide a brief explanation of each maturity measure to help participants select the appropriate level (these levels are presented in Table 26). Level 1 presents the basic requirements of the measure and the maturity levels increase to reach level 10 when the measure is most advanced.

Throughout the tests, only three levels of maturity were selected by participants for the graphics category (highlighted in grey in Table 26), namely, level 7, as in Project D, level 8, as in Projects B, C, E and G, and level 9, as in Projects A and F. Accordingly, this means that 3D models are applied in all CSPs, which reflects a shift in these practices from the conventional 2D design into 3D object-based modelling. Indeed, the "fundamental subtlety that makes a building model a BIM model (rather than, say, a CAD model) is the object orientation and the symbolic information linked to the geometry" (Demian & Walters, 2014).

However, level 10 Graphical Information has not been reported in any of the examined projects, which requires adding time (4D) and cost (5D) to the 3D model. Across all CSPs, the highest level achieved in 'Graphical Information' is level 9 (adding 4D) applied only in two projects scoring 8.4 points in Projects A and F. The implementation of BIM in industry is advancing in Graphical Information and shifting towards sharper and more intelligent 3D models.

Table 26 Ten levels of maturity of Graphical Information

Level of maturity	Description
Level 1	There are no graphics in the BIM-only text
Level 2	2D drawings are stored in the BIM but there is no interaction with information – the drawings are were not developed with the NCS
Level 3	The drawings stored were developed with NCS yet are still non-intelligent and not object oriented
Level 4	The drawings are 2D but are intelligent - a wall recognizes itself as a wall with properties but they are as designed and not as built
Level 5	The drawings are 2D and are intelligent - a wall recognizes itself as a wall with properties and they are as built but not current
Level 6	The drawings are 2D and are intelligent - a wall recognizes itself as a wall with properties and they are current
Level 7	The drawings are 3D object based and have intelligence
Level 8	The drawings are 3D object based and have a process in place to keep them current
Level 9	Time phasing has been added to the drawings to that one can see historical as well as being able to project into the future
Level 10	The drawing stored in the BIM are intelligent and object based and include time and cost information

6.2.3 Comparing the findings with a previous study in the literature

A similar study was carried out in 2012 by researchers in the U.S. In their study, they evaluated eleven award-winning projects using NBIMS-CMM, Version 1 (McCuen et al., 2012). The average score of these projects was 50.7 points, 6.1 points less than the average score of the seven UK based CSPs examined here by the author. However, despite having lower score, the U.S. projects are allocated to Certified maturity level which is higher than the maturity level of the UK projects (Minimum BIM). The reason for this is that the NIBS have designed the 'Minimum BIM' level to increase continuously. In Version 1, Minimum BIM ranged from 30 to 49.9 and in Version 2 from 40 to 59.9 (Table 27).

Therefore, while the average score in the U.S was 50.7 with ‘Certified’ in 2012, the score in the UK averaged 56.8 with only ‘Minimum BIM’ in 2014. However, this pre-defined increase of minimum BIM levels of maturity has been criticised by other researchers who argued that the BIM maturity of businesses should not be pre-established by the NIBS in a linear fashion based on calendar year (Succar, 2009b).

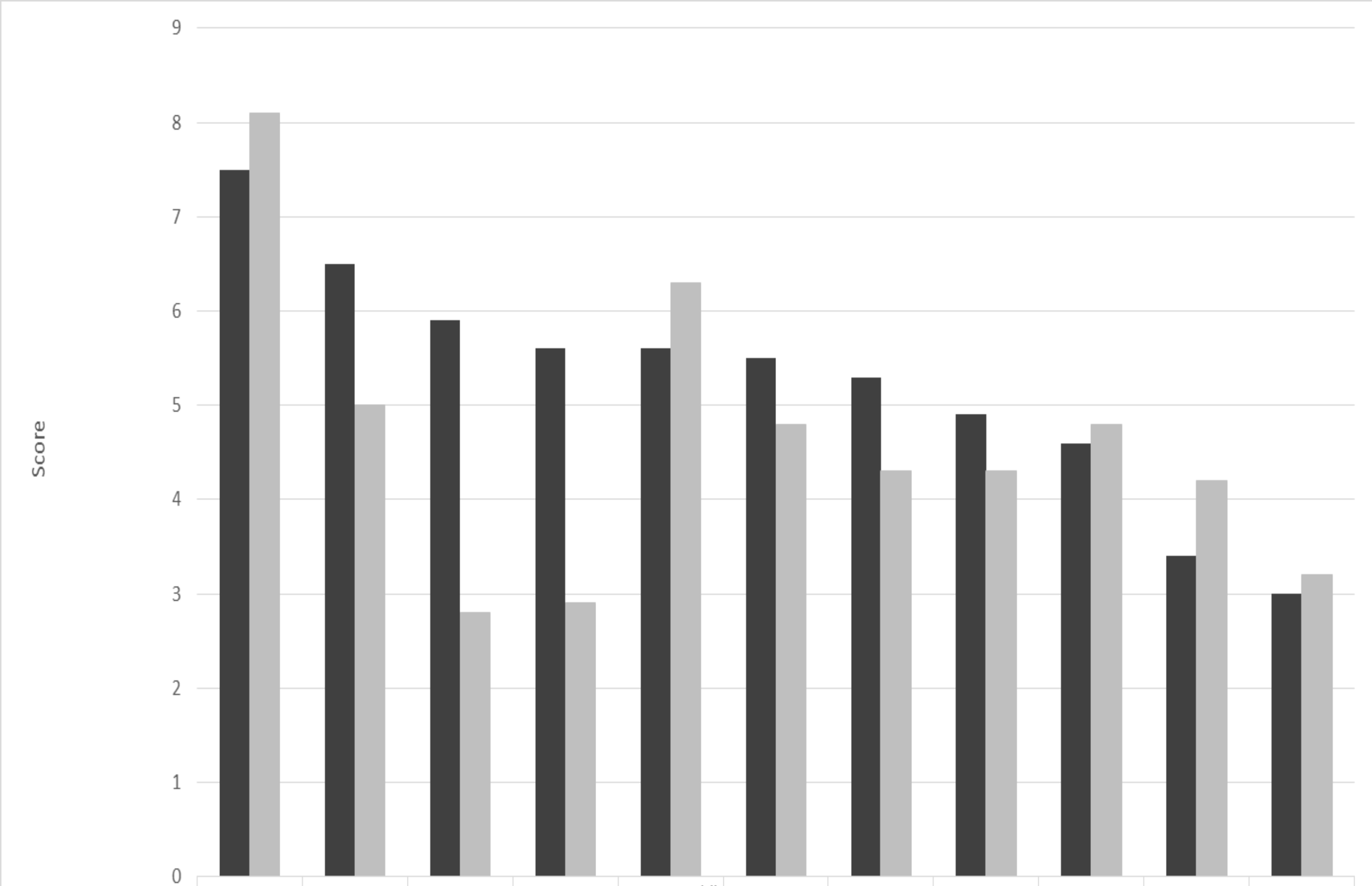
Table 27 Comparing the levels of maturity between the NBIMS-CMM Version 1 and Version 2

BIM level of maturity	**NBIMS-CMM Version 1**		**NBIMS-CMM Version 2**	
	Low	**High**	**Low**	**High**
Minimum BIM	30	39.9	*40*	*49.9*
Minimum BIM	40	49.9	*50*	*59.9*
Certified	50	69.9	60	69.9
Silver	70	79.9	70	79.9
Gold	80	89.9	80	89.9
Platinum	90	100	90	100

Interestingly, despite the differences between the scores of the two countries, projects in both the U.S. and the UK are most advanced in the ‘Graphical Information’ category, scoring 8.1 and 7.5 points respectively. Similar to the finding in this thesis, the Graphical Information maturity levels in the U.S. ranges between level 7 and level 9. Comparison of the average scores between the two countries shows that maturity levels are similar in several measures, such as, “Data Richness” and “Life-cycle Views” and “Roles or Disciplines” as presented in Figure 35.

However, the UK levels of maturity are higher than the ones in the U.S. in six measures. Major differences in scores can be found in two measures where the average scores in the UK are nearly twice those of the U.S. These measures are Change Management and Spatial Capability.

Country-to-country comparisons engender the understanding of BIM maturity on international levels. They provide professionals, researchers and policy-makers with a holistic snapshot of BIM performance in the industry.



	Graphical Information	Information Accuracy	Change Management	Spatial Capability	Interoperability/ IFC Support	Data Richness	Delivery Method	Timeliness/ Response	Roles or Disciplines	Business Process	Life-cycle Views
Average Score UK	7.5	6.5	5.9	5.6	5.6	5.5	5.3	4.9	4.6	3.4	3
Average Score U.S.	8.1	5	2.8	2.9	6.3	4.8	4.3	4.3	4.8	4.2	3.2

Figure 35 Comparison of the BIM average score between the UK and the U.S.

6.2.4 Discussion

It has been continuously reported that “BIM is the process rather than the technology” (Gilkinson et al., 2014). They have also stressed the need to understand the interlocking fields of BIM that combine processes, technologies and policies together, rather than focusing on one of its multiple-dimensions, as discussed by Succar (2010a). Despite this, findings in this thesis, Table 25, show low scores in ‘Life-cycle Views’ and ‘Business Process’ categories which have almost half the score of Graphical Information. This is also similar in the U.S. study. In all CSPs, BIM implementation was focused on specific measures, such as ‘Graphical Information’ and ‘Information Accuracy’, but far less attention was given to processes. A possible explanation is that professionals in industry are still treating BIM as a tool and technology rather than addressing the full agenda of BIM. The AEC industry, therefore, should ensure that their implementation of BIM addresses its multidimensional aspects that include processes, technologies and policies.

The seven CSPs outlined in Phase 1 present a brief snapshot of the AEC industry’s implementation of BIM. BIM utilisation in practice seems to be positive. In all CSPs, 3D object based models were applied. Moreover, each of these projects scored at least ‘Minimum BIM’, which means that all groups within these practices are considered to be working on what NIBS (2007) coined ‘true BIM maturity’. For the projects in this work, one exception can be found in Project D with a ‘Certified’ level of maturity.

An emerging use of BIM-AMs is now concerned with examining the BIM implementations across countries, which this chapter has compared the eleven measures of NBIMS-CMM between the U.S. and the UK. A similar study was carried out by Kam (2013) that applies the VDC Scorecard to 130 CSPs, contrasting and examining countries depending on their BIM adoption. Their testing enabled them to identify BIM maturity in countries against four major evaluation areas, namely, planning, adoption, technology and performance. For instance, their research found that Singapore leads the way in planning whilst U.S. is leading in adoption. This emerging use might lead to more research that changes the emphasis of BIM-AMs, from evaluating projects within an organisation into a broader approach that compares BIM levels nationally and internationally. Comparisons of large-scale dataset will be beneficial to evaluate what countries have accomplished in terms of BIM implementation and investigate what is needed for them in order to improve their maturity levels.

6.3 Phase 2: two different participants applying one BIM-AM to a single project (user comparison)

In Phase 2, the same project was assessed by two participants who had worked on the project being evaluated. The reason behind this approach is the need to observe how subjective or objective the AM is in practice.

Assessment of an 'Opera House' project was carried out, in association with a UK-based structural engineering practice. In this case, a senior structural technician (Participant 1), and a graduate engineer, (Participant 2), were both using BIM on the Opera House project, which was at the time of the interview (27/07/2014), moving into the construction stage. Both participants were unaware of the existence of BIM-AMs before this investigation. Therefore, a brief background to BIM-AMs was given prior to the assessment. BIM technology was implemented in this project as a unified platform between all stakeholders (using Autodesk Revit). Each of the participants took nearly 20 minutes to complete the hard copy of the NBIMS-CMM assessments. Their answers were later applied to the Interactive CMM (I-CMM). A table and a diagram, (Figure 36), were automatically generated, providing visual representation of the scores.

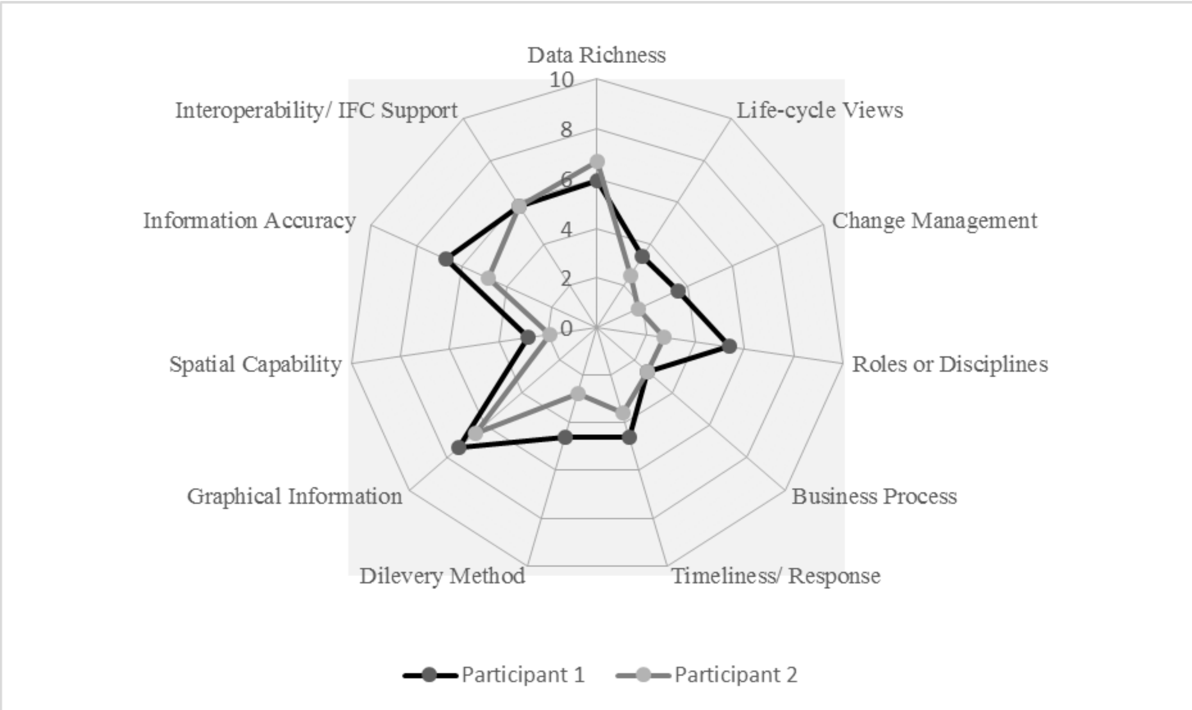


Figure 36 Areas of Interest Diagram - Completed by Participant 1 and Participant 2 (Adapted from: NIBS, 2007)

Physically, the two participants were located in the same office, sitting next to each other and working on the same project. Despite this close working relationship, their scores were noticeably different when they completed the same assessment of the same project. Table 28 shows a comparison of the score distribution of the eleven measured areas given by participants, and highlights, in grey, categories of equal rank order.

Table 28 Capability Maturity Model Scores for the same project with different participants

Area of Interest	Rank order	**Participant 1**	Rank order	**Participant 2**
Data Richness	3)	5.9	1)	6.7
Life-cycle Views	8)	3.4	8)	2.5
Change Management	7)	3.6	10)	1.8
Roles or Disciplines	5)	5.4	7)	2.7
Business Process	10)	2.7	7)	2.7
Timeliness/ Response	6)	4.6	5)	3.6
Delivery Method	6)	4.6	6)	2.8
Graphical Information	1)	7.4	2)	6.5
Spatial Capability	9)	2.8	9)	1.9
Information Accuracy	2)	6.7	4)	4.8
Interoperability/IFC Support	4)	5.8	3)	5.8
Overall Score		52.8		41.8
Level of maturity		Minimum BIM		Minimum BIM

The overall score given by Participant 1 (52.8%) is nearly 10 points more than Participant 2 (41.8%), reflecting how different results can be given on the same project. Answers for almost all the categories provided by the two participants were different, except in two cases; 'Business Process' and 'Interoperability', which were scored by both participants as 2.7 and 5.8 respectively. The most remarkable difference between the scores could be found in the 'Roles and Disciplines' category, with a discrepancy of nearly 3 points. Despite the descriptions defining each of the 11 measures (provided by the NIBS), the two participants understood some of the terms differently. Participant 2 argued that areas of interest in this AM were subjective and not numeric as in BREEAM. Therefore, the differences in answers might be related to the lack of clarity of terms used in the tool.

In comparing the data provided by both participants, some similarities can be found. Both allocated the project to a Minimum BIM level of maturity. Furthermore, it seems that both participants share roughly similar expectations of areas of strengths and weaknesses. This could be seen when comparing the two 'areas of interest charts' in Figure 36. The resulting scores seem to follow a similar pattern, with both participants rating the same criteria high and low, albeit with different absolute score values. One of the highest scores that both participants gave was in the 'Graphical Information' category (scoring 6.5 and 7.4 respectively) in line with Phase 1. This means that both agreed that they were providing all stakeholders with 3D object-based models which have intelligence. Another example of similar ranking order can be found in the 'Life-cycle views', 'Delivery Method' and 'Spatial Capability' area, where both scored the latter as the 9th weakest category in their answers (highlighted in grey in Table 28). What is of concern is that the same project achieved two different absolute scores from two participants working in the same office. This raises the question of how subjective this AM is. It also calls into question the clarity of descriptions in the tool. The 'Opera House' case draws attention to the need for an accurate BIM-AM where projects can be evaluated objectively by different assessors and still lead to a similar score.

6.3.1 Summary

In Phase 2, participants explained their attitudes towards the advantages and disadvantages of AMs in general and about the NBIMS-CMM in particular. Both agree on the need for assessments which according to them are "very good for marketing". Companies can report their current BIM maturity levels in projects and demonstrate their compliance with BIM requirements. This would in turn help clients select favourable practices and ensure that certain BIM measures are delivered in a particular desired way. In contrast, participants were concerned about the practicality of the AM. Participant 1 explained that AMs should be practical and easy to implement, otherwise they will result in lack of interest. This is similar to what is reported in the previous chapter which suggests that AMs should be applicable and easy to use (Succar et al., 2012). In addition, one of the challenges of AMs, according to Participant 1, is the "danger" to become a bureaucracy and shift towards being a planning requirement for the publicly funded projects, similar to the mandatory of BIM Level 2. This concern has not been currently reported in the reviewed BIM literature, but perhaps future developments of BIM-AMs might take that direction. In the building environmental AMs, BREEAM, for instance, was initially introduced as a voluntary assessment, and has been later adopted as a 'mandatory mechanism' for all government projects, as cited by Schweber (2013).

6.4 Phase 3: The same participant applying two BIM-AMs to the same project (model comparison)

This section describes the implementation of two different BIM-AMs on the same project by the same person. Most studies of the use of BIM-AMs focus only on implementing one method, and no single study exists which adequately assesses the same project using two different BIM-AMs. In Phase 3, both the NBIMS-CMM and the VDC Scorecard were applied to the same project in order to examine whether they give consistent assessments. This scenario was implemented in two CSPs. It is important to note that the VDC Scorecard, (Version 1.3), is a very detailed tool, which includes four main areas: planning, adoption, technology and performance. To complete the full assessment takes a couple of hours. However, in Phase 3, only the 'technology' part of the tool was completed, since it was difficult to find participants who were willing to spend two hours to complete an assessment. Additionally, the selected part of the AM is the closer to the areas assessed by NBIMS.

The first CSP in this phase was a 'private schools' project in a global consulting organisation that provides planning, design and construction services in the UK. A principal BIM integrator completed the two different AMs assessments for the same project. The project consisted of a group of schools and, at the time of the interview, (04/06/2014), it was moving to the construction phase. However, the answers provided by the participant were based on the schematic design phase. The BIM Software application used for this project was mainly Revit, and drawings were saved as PDFs to share them with other stakeholders. When completing the NBIMS-CMM, the overall score was 52.9, points obtaining a 'Minimum BIM' as a level of maturity, with 7.2 more points required to achieve BIM certified (Table 29). Analysis of the data provided by the participant for this project scored high levels for 'Graphical Information', 'Change Management' and 'Information Accuracy', with far fewer points allocated to the other categories.

In a second stage, the same project was evaluated again by the same participant using the VDC Scorecard, 'technology' part. The overall score in this case was 66%, which brought it to 'Advanced Practice' classification as in Table 29. Areas of measurements in this AM were varied, detailed and in a few occasions numeric. An example of these measures is the percentage of 'information loss after model exchange'. For this specific measure, the participant pointed out confidently that there was 0% loss of information while sharing models between architects and engineers. An explanation for this was the fact that all members involved in this project used the same piece of software (Autodesk Revit) covering differing uses such as 3D modelling and rendering. From this model, DWG and PDF files were extracted and then circulated at project management level providing construction and cost documents. In other practices, different software platforms are used and exchanging models between different platforms might lead to loss of information.

Table 29 Obtained scores applying NBIMS-CMM

The Interactive BIM Capability Maturity Model			
Area of Interest	**Weighted Importance**	***Choose your perceived maturity level***	***Credit***
Data Richness	84%	Data w/Limited Authoritative Information	*5.0*
Life-cycle Views	84%	Add Construction/ Supply	*2.5*
Change Management	90%	Full Optimization	*9.0*
Roles or Disciplines	90%	Partial Plan, Design&Constr Supported	*4.5*
Business Process	91%	Some Bus Process Collect Info	*2.7*
Timeliness/ Response	91%	Data Calls Not In BIM But Most Other Data Is	*2.7*
Delivery Method	92%	Network Access w/ Full IA	*3.7*
Graphical Information	93%	3D - Current And Intelligent	*7.4*
Spatial Capability	94%	Spatially Located	*2.8*
Information Accuracy	95%	Comp GT w/Limited Metrics	*8.6*
Interoperability/ IFC Support	96%	Limited Info Transfers Between COTS	*3.8*
	National Institute of BUILDING SCIENCES Facilities Information Council National BIM Standard	**Credit Sum**	**52.9**
		Maturity Level	Minimum BIM

ADMINISTRATION	**Points Required for Certification Levels**		
	Low	**High**	
	40	*49.9*	*Minimum BIM*
	50	*59.9*	*Minimum BIM*
	60	69.9	**Certified**
	70	79.9	**Silver**
	80	89.9	**Gold**
	90	100	***Platinum***
Remaining Points Required For:		Certified	7.2

A similar scenario was seen in another CSP, a university building project in another practice located in the UK. Results in this case were roughly similar to the findings of the previous case study and, therefore, are briefly discussed here. The project was assessed applying both NBIMS-CMM and VDC Scorecard. In the first stage, the project scored an overall of 51 points when applying NBIMS-CMM, which categorised it to 'Minimum BIM'. This AM was completed by Participant A, who ran the project. However, Participant B, an architect, completed the VDC Scorecard on the same project allocated an overall score of 64% and classified it as 'Advanced Practice'. Developers of the VDC Scorecard established a 'confidence level' in case participants were uncertain about their answers. This was applied in this case with a confidence level of 83%. The findings of the two CSPs can be seen in Table 30.

Table 30 Comparing the Results of Two AMs on Same Project

BIM-AM/Case study	Private Schools Project	University Building Project
NBIMS-BIM	52.9 points, 'Minimum BIM'	51.0 points, 'Minimum BIM'
VDC Scorecard	66%, 'Advanced Practice'	64%, 'Advanced Practice'

6.4.1 Summary

Phase 3 provides examples of applying two BIM-AMs on the same project. The only difference is that in test 1, the same participant completed the two different assessments, whilst in test 2, two different participants completed the assessments. In both cases the scores reported by completing the two AMs were significantly different. When NBIMS-CMM was applied to either project, a 'Minimum BIM' level was achieved, which is the lowest level the tool provides. In contrast, when assessing the same project with the VDC Scorecard, the project ranked 'Advanced Practice' in both cases, which is the third level of maturity out of five (Table 31).

Table 31 Levels of Scoring System in NBIMS-CMM and VDC Scorecard

NBIMS-CMM (Version 2)	Minimum BIM (40-59.9)	Certified (60-69.9)	Silver (70-79.9)	Gold (80-89.9)	Platinum (90-100)
VDC Scorecard (Version 1.3)	Conventional Practice (0-25%)	Typical Practice (25-50%)	Advanced Practice (50-70%)	Best Practice (70-85%)	Innovative Practice (85-100%)

This rather contradictory result may be due to a number of differences. The first is related to issues of the simplicity and complexity of BIM-AMs. NBIMS-CMM is a short, simplified tool whereas the VDC Scorecard is much more detailed and requires more time and information to be completed. In NBIMS-CMM, 11 areas were assessed. For each of these areas, participants had to choose one maturity level ranging between 1 to 10 points (10 is the highest maturity). Thereby, participants had to provide only 11 non-numeric answers to complete the AM. In contrast, the VDC Scorecard, 'technology' part, assesses 12 areas, although only five of them are actually included in the calculation of the overall score, namely highest level of detail, data sharing method, information loss after model exchange, starting phase and ending phase. Unlike the NBIMS-CMM, each VDC area covers 19 factors. This means that respondents were required to provide 19 × 12 = 228 answers for VDC Scorecard compared to 11 in NBIMS-CMM. The second possible cause of the different scores is the difference in measures assessed. The two BIM-AMs address different areas of technology. 'Information Loss After Model Exchange', which is one of the main principles of BIM, was assessed in VDC Scorecard but not in the NBIMS-CMM. Overlap between the measures of the two AMs is identified only in three categories (Table 32).

Table 32 Comparison of Areas of Interest between VDC Scorecard and NBIMS-CMM

NBIMS-CMM	VDC Scorecard
Data Richness	Highest Level of Detail
Delivery Method	Data Sharing Method
Interoperability/ IFC Support	Model Exchange Format
Life-cycle Views	Model Uses Utilised
Change Management	Primary Software
Roles or Disciplines	Secondary Software
Business Process	Information Loss After Model Exchange
Timeliness/ Response	Starting Phase
Graphical Information	Ending Phase
Spatial Capability	Number of Stakeholders creating or Using Model/File
Information Accuracy	Number of Members creating or Using Model/File
	Stakeholder Leading Effort

6.5 Discussion and conclusion

AMs are essential to illustrate how BIM is being implemented internally, within the same company, externally, when compared to other businesses and more broadly, internationally across countries. It has been observed in the literature that there is still uncertainty and a lack of a shared vision of what is BIM. This impacted the current AMs that contain different range of measures and provide different levels of complexities. The chapter builds on a novel testing approach that aims to understand some questions surrounding the methods of measuring BIM in projects. It provides three perspectives on BIM measurement that are concerned with score comparison (Phase 1), user comparison (Phase 2) and model comparison (Phase 3).

If a wide range of projects are evaluated by applying the same AM, then an overall view of BIM implementation can be better understood. In Phase 1, Section 6.2, the application of NBIMS-CMM to the seven projects shows that all projects are 'BIM' projects since all of them are allocated to at least "Minimum BIM"; the lowest required maturity level by the NIBS to be addressed as a BIM project. It has been seen that BIM's levels of maturity are different across different organisations and across projects of the same organisation, as in Projects D and E of Company 3.

The AEC industry seems to be most advanced in Graphical Information when compared to other evaluated measures in NBIMS-CMM; similar to what is being observed in the U.S. study (Section 6.2.3). This means that evaluated projects in both countries are applying 3D models rather than relying solely on 2D traditional drawings. This also confirms the definitions of BIM provided by several scholars and institutions who define BIM as 3D representation of buildings (alongside other elements of BIM), discussed in Section 1.1. The industry, however, should emphasise the different aspects of BIM to achieve its full potential instead of focusing on one side of it. That is why several scholars, including Succar, highlight the need to understand BIM as a set of processes, policies and technologies.

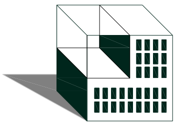
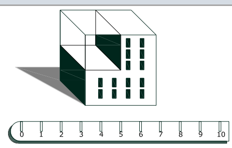
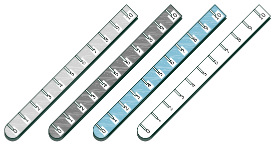
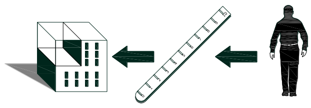
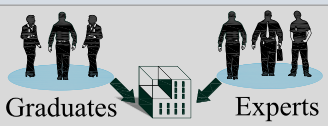
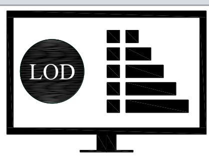
The tests undertaken in this chapter have shown how different current AMs are and how they can result in contrasting outcomes. The same project can be allocated to a lowest level when assessed by one method and a high maturity level when evaluated by another. The two applied AMs, the NBIMS-CMM and the VDC Scorecard, present different ways of defining the criteria of BIM; they have different focus and priorities. Therefore, the outcomes of the same project assessed by these AMs were significantly different and difficult to compare.

Two main points are raised in this chapter. The first considers the consistency of current AMs. For the case study of the Opera House in Phase 2, Section 6.3, two different scores have been obtained when evaluated by two different participants using the same AM. The second point raises the question of which AM to trust. The Private School and the University Building Projects assessed in Phase 3 show how two different AMs result in two contrasting maturity levels for the same project. However, rather than arguing which AM is the 'best' to use, it is more important to focus on the way they are used, by applying them intelligently as a useful source of information that influences the decision making processes within businesses.

These two points will be further explored in Chapter 7. Most previous studies focus on BIM performance measurement as technical and practical features of the AM rather than the 'people' who are responsible for implementing the AM in practice. Chapter 7, therefore, addresses this gap, by focusing on the relationship between the outcomes of the scores and the background of the participants completing the assessment.

7 Comprehensive testing approach of current BIM-AMs

The application of two BIM-AMs was initially examined in Chapter 6 in three different phases. However, in this chapter, a series of tests are described in two detailed Case Study Projects (CSPs). The NBIMS-CMM, the VDC Scorecard and the BIM-MM (discussed in Chapter 4) are used in all tests. This additional and broader implementation of BIM-AMs is also supplemented with results of a survey and interviews that explore professionals' awareness of BIM-AMs and their attitudes towards these assessments.

1: Introduction	2: PMSs	3: BIM-AMs
		
Main questions included: What is BIM? What is the need for BIM-AMs?	Includes: - Brief history of the broad PMSs, their definitions - PMSs roles and barriers - Sample of PMSs	- Explains the wide range of BIM-AMs, their evolution, opportunities and challenges - Investigates how BIM-AMs have been informed by the broader PMSs
4: Research methodology	**5: Perspectives on BIM-AMs**	**6: Pilot Testing**
		
Introducing the chosen research methods including questionnaire, interview and the implementation of multiple AMs in practice	- Critical analysis of the BIM-AM, their similarities and differences - This includes the design process, the complexity and the range of measures	Initial testing of individual and multiple AMs in practice in association with a number of practices
7: Comprehensive testing	**8: Automated BIM-AM**	**9: Conclusions**
		
In association with Arup, applying three AMs to the same project and completed by six participants who have different BIM experience i.e. experts and graduates	Includes: - The need for automated AMs - The implementations of BIM-AM in practice	Current perspectives and future directions of BIM-AMs

7.1 Survey

In parallel with the examination of BIM-AMs in practice, a survey was carried out at Arup and also at 'The Future of BIM: Looking beyond 2016' conference. In total, 40 questionnaires were completed, as explained in Chapter 4. Two primary themes of particular importance were identified; namely, the awareness of BIM-AMs and the importance of AMs in the BIM domain. The survey questionnaire was built on the literature review and discussed a number of points, including the need for BIM-AMs, whether participants are aware of AMs or not, and their opinion on the completed assessments. To complete the survey questionnaire, participants spent 10-15 minutes each to provide their answers (see Appendix C).

7.1.1 Awareness of BIM-AMs

When asking participants if they were aware of any of the current BIM-AMs, a total of 12 respondents answered 'yes' (30%), compared to 28 respondents who answered 'no' (70%). This reflects the lack of awareness of the available BIM-AMs. However, those who answered 'yes' were then asked to write down the AM(s) they are aware of, without Analysis of the results revealed that the top three recognised AMs were the BIM-MM (Arup, 2014), the BIM Maturity Matrix (Succar, 2010a) and the NBIMS-CMM (NIBS, 2007) (Figure 37).

The most recognised AM was BIM-MM, which was reported by nine participants. A likely explanation is that seven out of nine of those aware of BIM-MM are currently working in Arup, and therefore they would be familiar with their in-house model. Furthermore, the BIM-MM was developed by a global company, released at Autodesk University in late 2014 and has been made available on-line for public use (Arup, 2014). It is currently the only UK-based model that evaluates projects. Since its release, the BIM-MM has been constantly publicised at different events including the Institution of Civil Engineers, the Chartered Institution of Building Services Engineers (CIBSE) Journal (CIBSE, 2015) and in some academic journals (Chen, 2015; LIN et al., 2015; Won & Lee, 2016).

The second most recognised AM was the BIM Maturity Matrix developed by Succar (2010a) (see Section 3.6.1). Since 2007, Succar carried out extensive research on BIM with particular focus on performance measurement, BIM capabilities, competences and BIM maturity levels across countries. Succar's work has been widely recognised and acknowledged in the BIM arena (Succar, 2009a; Succar et al., 2012). The third most recognised AM is the NBIMS-CMM, perhaps because it was the first BIM-AM to be developed and because its developers have constantly updated the model, with three versions to date (NIBS, 2007, 2012, 2015). Some of the current AMs were not reported at all by any participant. It was found that only 30% of the participants were aware of any AM despite being all experienced in BIM either as researchers or practitioners.

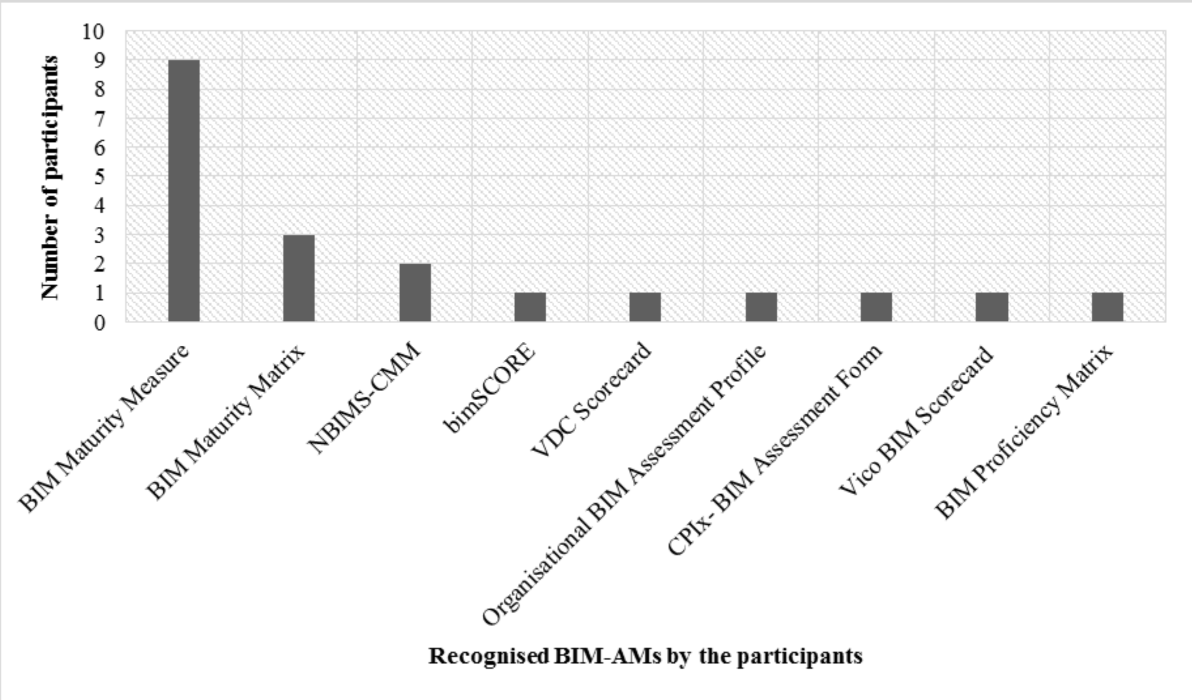


Figure 37 Awareness of BIM-AMs according the 41 completed questionnaires

7.1.2 The need for BIM-AMs

Despite the lack of awareness of current AMs, the survey results reveal general agreement by participants on the importance of performance measurement. When asked about the need to evaluate BIM, participants had to select one of five answers, namely, ‘strongly agree’, ‘agree’, ‘neutral’, ‘disagree’ or ‘strongly disagree’. The results show that 26 participants ‘agree’ and 14 participants ‘strongly agree’ with the need for BIM evaluation. This was followed by asking participants to express their opinions on the need for measuring BIM in an ‘open-ended’ question. This enabled participants to explain their ideas without restricting them to any pre-selected responses (Fellows & Liu, 2009).

Analysis of the data is presented in Figure 38, which shows that professionals use BIM-AMs for eight reasons; to explore opportunities and challenges, compare with different companies, explore progression, measure return on investment, measure capabilities of workforce, establish effective feedback, set targets to achieve and inform training.

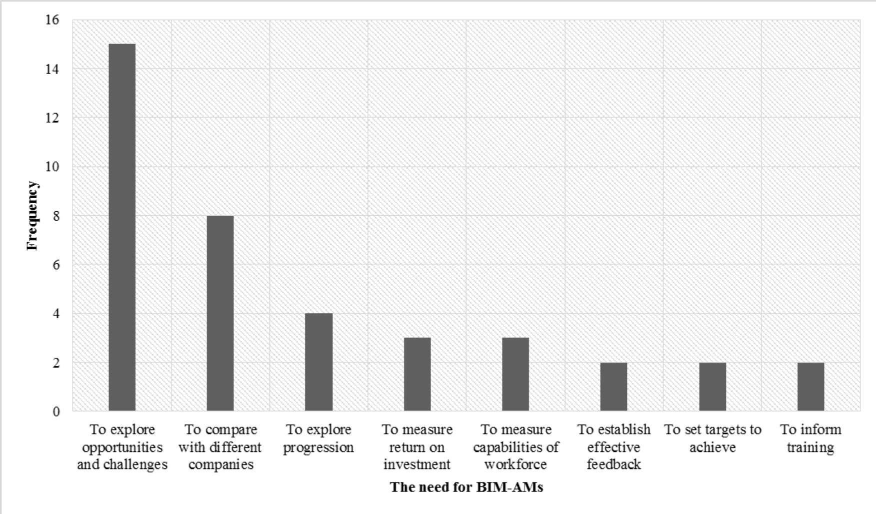


Figure 38 What is the importance of measuring the implementation of BIM? Top eight reasons

Exploring opportunities and challenges emerges as the most popular reason for measuring BIM according to the survey. AMs enable professionals to observe the "breadth and totality" of the business as a whole (Kaplan & Norton, 1995). By observing their internal business processes and assessing their current BIM capabilities, companies can identify their strengths and limitations. This finding seems to match those observed in previous studies such as Morlhon et al. (2015) and Succar et al. (2012), as discussed in Section 3.3. It is also highlighted by Interviewee 9 (Section 4.1.4, a BIM development manager) who explains:

> "If we are only measuring our businesses as a whole, how can we identify the part that our business that are doing well, and the parts of our business that are not doing so well and need additional help. So that is the reason why we felt that we need to focus on measuring projects so that we could say 70% of our projects were achieving this certain score and that means that 70% of our company is doing BIM to the degree that we want to."

Another important finding was that AMs are needed to support professionals comparing their BIM utilisation with different companies across the AEC industry. This finding, ranked number two, is in line with those in previous studies in literature. Succar et al. (2012) and researchers at the CIC research programme (CIC, 2013), indicate that performance measurement assists professionals to see where they stand in the industry. As Graduate 3 (participant in Project B from Arup, an associate director) explains that "[BIM-AMs] enable understanding of where we stand in industry on route to achieving full potential use of BIM". This has also matched what interviewee 2, a BIM Champion (Section 4.1.4), noted "I think as a business you always want to sort of see where you sit with your fellow businesses".

7.1.3 Discussion

"Why measure performance" has been the subject of considerable research in the broad literature of performance measurement (section 3.2). This is exemplified in the work of Kaplan and Norton (2005) who explain how measures can help companies move forward, the eight reasons to measure performance defined by Behn (2003), and the extensive work carried out by Neely (1999) on performance measurement. Such studies, in addition to the support of policy-makers and professionals, have resulted in a considerable success and a widespread awareness of AMs in many research fields, such as the building environmental assessments (Cole, 2005).

In the BIM research agenda, the implementation of AMs is still lagging behind other performance measurement systems in other research fields (Kam et al., 2013b). However, despite the lack of both implementation and wide recognition of BIM-AMs, participants in the survey and the interviews have shown general agreement on the need for assessments. Their opinions and attitudes varied significantly. Some of them believe that measurement is a necessity. They have however, linked this necessity with the Government BIM Level 2 mandate. As Interviewee 8, a senior lecturer, explained:

> "Why do we have to measure the implementation of BIM, I think it is probably a simple necessity to enforce the government mandate. I don't think anyone can argue with that. And the government mandate is necessary to enforce the implementation of BIM and to get those cost savings and efficiency improvement in the construction industry. So you know everybody needs to be maturity Level 2 and maturity Level 3 in the future of BIM. And the government needs to check that for people bidding for public sector projects and therefore we need to have this assessment method."

Other interviewees highlighted the need for AMs to inform the delivery process of BIM implementation. They explained how important these models are in understanding a business's current BIM level and how it can improve. As Interviewee 7, a design architect (Section 4.1.4) noted:

> "Yes I do think it would be beneficial [to have an AM] because it gives a guideline to where everyone within the process needs to be. What level of information needs to supply, what the purpose of the information is? I think it will be very important…I think those guidelines are critical because then you can specify, understand and comprehend what you need to do within your remit in the BIM sense but also in the delivery sense."

7.2 Collaboration with Arup

The CSPs in this chapter were conducted in collaboration with Arup, one of the most prestigious engineering companies globally. The collaboration was associated with the London office, Arup's headquarters, where BIM leads are based. The research was initially presented to the BIM development manager in April 2015, and later to two managers in June 2015. These meetings were crucial in introducing the research and developing the testing approach.

The company is interested in applying the most advanced concepts of BIM, including digital collaboration and intelligent 3D models with, in many cases, time (4D) and cost (5D) attached (Arup, 2014). It also has a particular interest in the field of performance measurement, as they have developed their own in-house AM, namely, the BIM Maturity Measure (BIM-MM). The company agreed to be involved in the research and provided two CSPs. Once the agreement with the company was confirmed, the BIM development manager selected twelve participants (including himself) and also specified two projects for the case studies. Unfortunately, one participant was unable to carry on with the study.

The testing includes two Case Study Projects (CSPs) with a total of 15 completed AMs; eight in the first CSP and seven in the second. In each CSP, three AMs are examined. Multiple CSPs produce credible and more powerful results than the data collected from one CSP. They also enable a wider array of evidence than do single cases. This broadened array builds on the collected findings of the CSPs, but at the same time, it treats each of the projects independently and then draws comparisons across them. No previous research in the BIM literature has compared multiple AMs on the same project, although this method has been applied to building environmental AMs, where three assessments were tested on the same project (Wallhagen & Glaumann, 2010).

7.3 Data collection and analysis

In terms of the BIM-AMs testing, the BIM development manager has specified two projects' teams to volunteer their time. Initial testing with the BIM development manager was carried out on the 8th of July 2015. This was followed by a testing plan and agenda that were sent to all participants on the 13th of July 2015. The selection of the CSPs was based on projects in which the company believed they were implementing BIM. The two CSPs were under construction at the time of the interview.

The first project is an office for a developer/contractor in central London, and the second is a new office building for a large broadcasting company west of London. In total, it took 12 hours to complete the assessments with the eleven participants. This included introducing the AM to each participant, carrying out the assessment and then discussing initial findings with them. Each CSP was divided into two rounds to explore the relationship between the participants' background and the AMs' outcomes. The two rounds, which took place on the 17th of July 2015 were (Table 33):

- **Round 1** engaging BIM 'experts' who have considerable experience in the BIM domain and construction business.
- **Round 2** included 'graduates' who had less experience in BIM.

Each participant completed one AM apart from one participant in each round, who used two AMs to assess the same project (Expert 2 and Graduate 2).

Table 33 Summary of tests in Chapter 7

		Participants	Job title	Years of experience
Project A	Round 1	Expert 1	Structural technician	12
		Expert 2	BIM development manager	7
		Expert 3	MEP tech leader	5
	Round 2	Graduate 1	Structural engineer	2
		Graduate 2	Mechanical engineer	3
		Graduate 3	Electrical engineer	-
Project B	Round 1	Expert 1	BIM coordinator	5
		Expert 2	BIM development manager	7
		Expert 3	Design engineer	2
	Round 2	Graduate 1	Could not take part	
		Graduate 2	Senior engineer	8
		Graduate 3	Associate director	2

The testing in Round 1 and Round 2 followed a similar approach. The difference between the two rounds, however, is that participants in Round 1 are 'experts' and in Round 2 they are 'graduates'. The scenarios undertaken in the two projects are illustrated in Figure 39, which presents the AM applied by each participant and their obtained overall score.

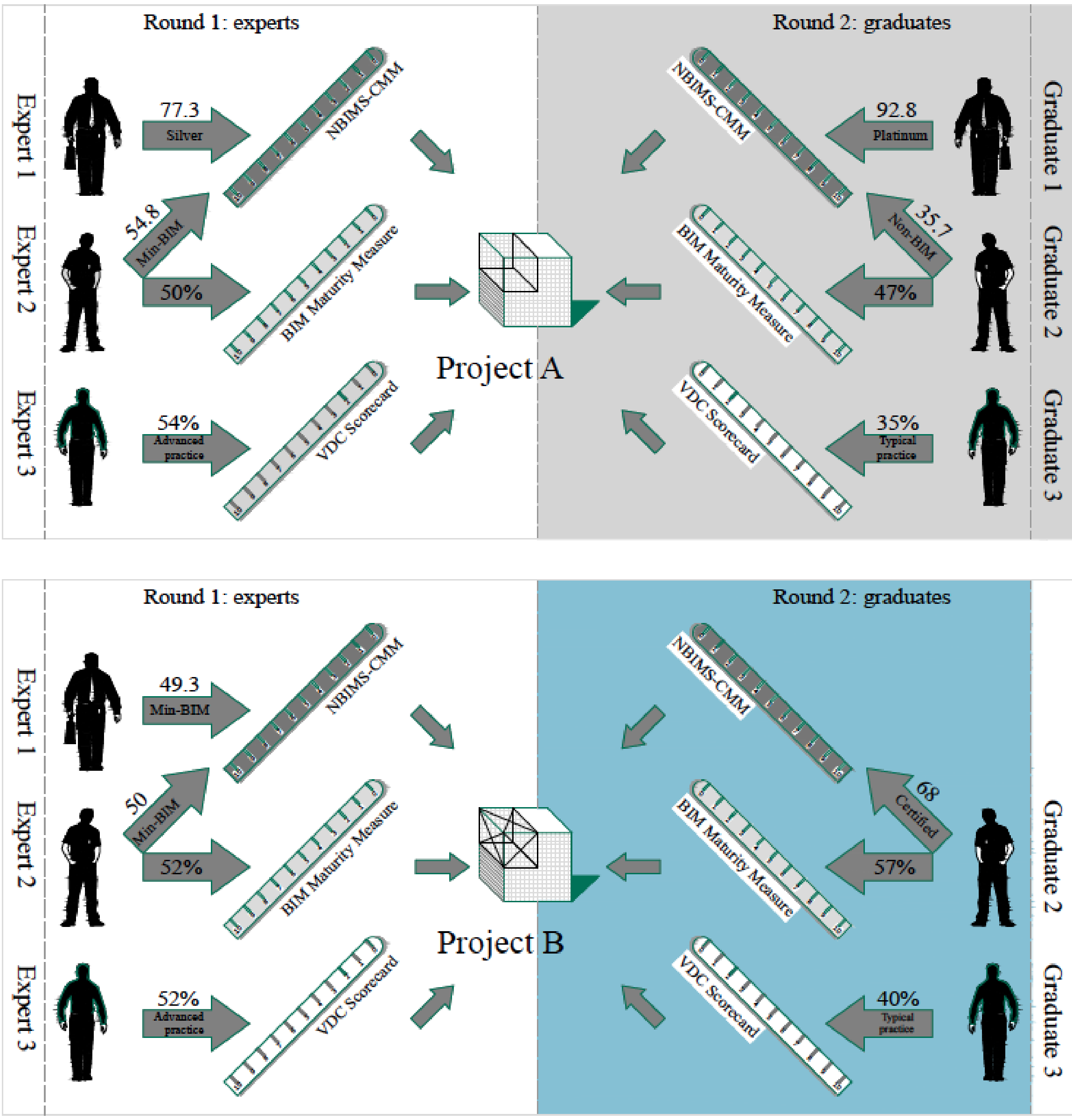


Figure 39 Project A (top) and Project B (bottom): comparing the results of three AMs used by eleven BIM professionals to evaluate the same project in two different rounds

The collection of data involved each participant carrying out a BIM assessment and completing a survey (except Graduate 3 in Project A). In the two projects, names of participants, clients and projects were all anonymised to maintain confidentiality. Each participant spent between 20-30 minutes to complete each of the AMs. An overall score was given to each project and allocated to a particular level of maturity defined in each AM (As seen in Table 34). Data from all assessments were mostly collected using the hard copies of the AMs. Once completed by participants, data was transformed to the electronic versions of the AMs in order to calculate final scores. However, some participants preferred to complete the electronic versions of the AMs and sent them back via email (such as, the BIM development manager who carried out four assessments). In addition, Expert 3 in Project B was located in Dublin, and therefore completed the survey and AM after a telephone discussion and email exchange. Then, all documents generated across all assessments were compared and analysed.

Table 34 Levels of Scoring System in NBIMS-CMM and VDC Scorecard

BIM-AM	**Maturity levels**				
NBIMS-CMM (Version 2)	Minimum BIM (40-59.9)	Certified (60-69.9)	Silver (70-79.9)	Gold (80-89.9)	Platinum (90-100)
BIM-MM	BIM-MM provides only an overall score without allocating the project to a certain level of Maturity. However, each measure has six levels of maturity to select from				
VDC Scorecard (Version 1.3)	Conventional Practice (0-25%)	Typical Practice (25-50%)	Advanced Practice (50-70%)	Best Practice (70-85%)	Innovative Practice (85-100%)

7.4 Findings

In both projects, scores were varied and contrasted. Whilst all four AMs completed by experts in Round 1 showed relatively similar scores, greater contrast between the scores was recorded in the AMs completed by graduates in Round 2. Analysis of this comprehensive testing is grouped into three categories in each round. For instance, in project A these categories are (Figure 39, top):

1. Two different participants applying one AM to a single project: Experts 1 and 2 applying NBIMS-CMM in Round 1 and Graduates 1 and 2 in Round 2
2. Same participant applying two AMs to the same project: Expert 2 applying NBIMS-CMM and BIM-MM to the same project in Round 1 and Graduate 2 in Round 2
3. Three different participants applying three AMs to a single project: Experts 1, 2 and 3 applying NBIMS-CMM, BIM-MM and the VDC Scorecard in Round 1 and Graduates 1, 2 and 3 in Round 2

For **Project A** eight assessments were completed by six participants. A similar scenario is applied in Project B, but with five participants instead of six. The results were similar in some occasions and extremely contrasted in others. The scores obtained by the 'experts' and by the 'graduates' are shown in Figure 39. In **Project A**, within the team who were involved in Round 1, the structural technician, the BIM development manager and the MEP tech leader, all had experience in BIM.

A comparison of the four scores obtained by the three participants and applying three different AMs reveals a number of common issues, both in the understanding of BIM implementation in the project and in the broader context of the three applied AMs. When applying NBIMS-CMM, Expert 1 recorded 77.3 points which allocate the project to 'Silver' BIM level of maturity (NIBS, 2012). However, in all the rest of the three completed AMs, the BIM scores were similar 54.8 "Minimum-BIM" using NBIMS-CMM and 50% "applying BIM-MM" (both completed by Expert 2) and 54% applying the VDC Scorecard by Expert 3.

To fully explore the results found in Round 1 and Round 2, it is necessary to explain the three following stages.

7.4.1 Two different participants applying one BIM-AM to a single project:

In Round 1 (experts), **Project A**, an important finding concerns the accuracy and subjectivity of NBIMS-CMM. Observations of the data provided by Experts 1 and 2 completing the same AM draws clear differences between the two scores, with Expert 1 giving just over 20 points more than Expert 2. Figure 40 shows a comparison of the scores obtained by Experts 1 and 2 across the eleven evaluated measures in NBIMS-CMM. Despite the contrast between the two overall scores, the results tend to follow a similar pattern. Both participants, for instance, agree that the implementation of BIM in this project is high in 'Information Accuracy', 'Interoperability/IFC Support', 'Change Management', 'Business Process', 'Delivery Method' and 'Graphical Information', and less advanced in 'Life Cycle Views' and 'Timeliness/Response'. However, in all measures, Expert 1 gave higher scores than Expert 2.

In Round 1 (experts), **Project B** the same activity was carried out. Unlike **Project A**, overall scores obtained by Experts 1 and 2 when completing the NBIMS-CMM are very similar with 49.33 and 50 points respectively (Figure 41). This allocates the two projects to the Minimum BIM maturity level. Most scores of the evaluated measures seem to be roughly similar between the two participants. Contrasted opinions can be found only on four measures, namely, Data Richness, Business Process, Graphical Information and Change Management. In these three measures, scores by Expert 1 are at least twice the scores obtained by Expert 2. The results in Round 1 Project B shows greater levels of agreement between participants when compared to the outcomes of participants in Project A. This might be due to the similar BIM roles between Expert 1 (BIM coordinator) and Expert 2 (BIM development manager) in Project B, whilst Expert 1 (structural engineer) in Project A might have less engagement in the BIM implementation as a whole.

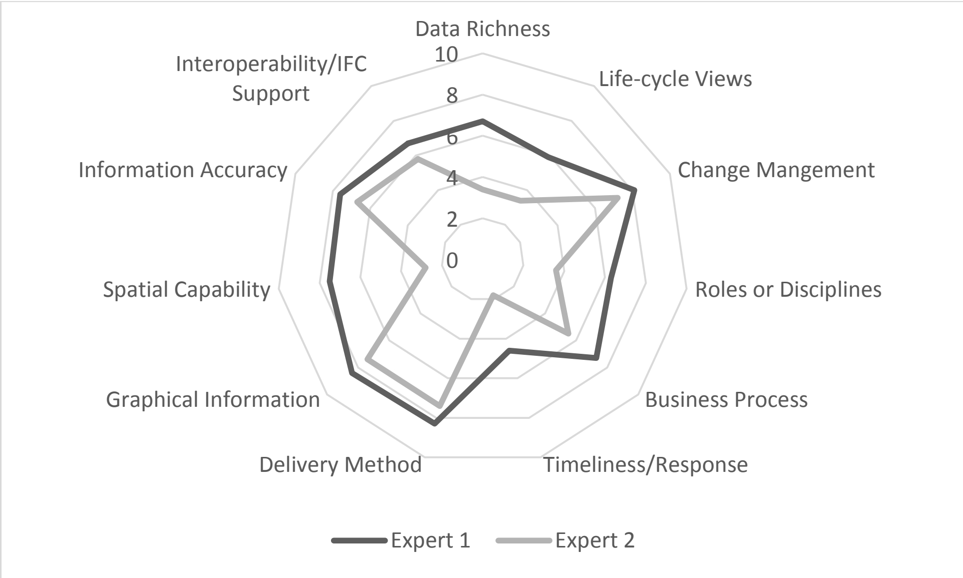


Figure 40 Project A, Round 1 (experts): A comparison of scores obtained by the two participants when applying NBIMS-CMM

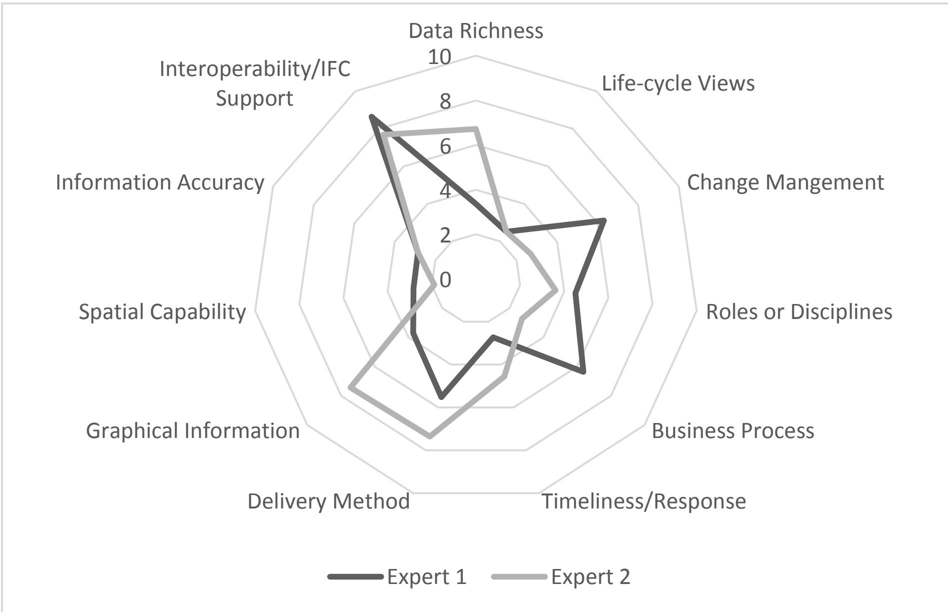


Figure 41 Project B, Round 1 (experts): A comparison of scores obtained by the two participants when applying NBIMS-CMM

In terms of the ranked order of measures in **Project A, Round 1**, participants share the same order in seven measures as presented in grey in Table 35. In Project B, only one area has the same rank order, Table 36. The greatest contrast between the two participants' scores can be found in 'Spatial Capability' with 7.5 points by Expert 1 and 2.8 points by Expert 2. The highest score recorded by the two participants is 'Graphical Information' (whereas it is Interoperability/IFC Support in Project B). The achieved maturity levels (out of 10, 10 is the highest) in 'Graphical Information' according to NBIMS-CMM are:

- Expert 1 scoring 8.4, Level 9: 'time phasing has been added to the drawings to that one can see historical as well as being able to project into the future'
- Expert 2 scoring 7.4, Level 8: 'The drawings are 3D object based and have a process in place to keep them current'.

Table 35 Capability maturity model for the same project with two different participants: Project A

BIM areas of interest	Rank order	Expert 1	Rank order	Expert 2	Difference
Graphical Information	1	8.4	1	7.4	1
Delivery Method	2	8.3	1	7.4	**0.9**
Change Management	3	8.1	3	7.2	**0.9**
Information Accuracy	4	7.6	4	6.7	**0.9**
Spatial Capability	5	7.5	10	2.8	**4.7**
Business Process	6	7.3	6	5.5	1.8
Interoperability/IFC Support	7	6.7	5	5.8	**0.9**
Data Richness	7	6.7	8	3.4	3.3
Roles or Disciplines	9	6.3	7	3.6	2.7
Life-cycle Views	10	5.9	8	3.4	2.5
Timeliness/Response	11	4.6	11	1.8	2.8
Overall Score		**77.3 Silver**		**54.8 Minimum BIM**	

Table 36 Capability maturity model for the same project with two different participants: Project B

BIM areas of interest	Rank order	Expert 1	Rank order	Expert 2	Difference
Interoperability/IFC Support	1	8.6	1	7.7	0.9
Business Process	2	6.4	8	2.7	3.7
Change Management	3	6.3	9	2.7	3.6
Delivery Method	4	5.5	3	7.4	1.9
Roles or Disciplines	5	4.5	6	3.6	0.9
Graphical Information	6	3.7	2	7.4	**3.7**
Data Richness	7	3.4	4	6.7	3.3
Information Accuracy	8	2.9	7	2.9	0
Spatial Capability	9	2.8	11	1.9	0.9
Timeliness/Response	10	2.7	5	4.6	1.9
Life-cycle Views	11	2.5	10	2.5	0
Overall Score		**49.3 Minimum BIM**		**50.0 Minimum BIM**	

This means that both participants agree that they are using 3D object based intelligent models in this project. The difference between the two scores in 'Graphical Information' is related to the implementation of scheduling (or 4D, time). Expert 2 explained during the interview that 4D is partly applied, but not across all the teams involved in the project, and therefore he did not select maturity level 9.

Although participants share same rank order in seven measures, none of the 11 evaluated measures was recorded to be the same between the two participants (in Project B, two areas are reported to have the same score: Information Accuracy and Life-cycle Views, highlighted in grey). The most likely reason for the differences between the two overall scores are firstly, the relative lack of BIM-AMs experience amongst the team and the job responsibilities of each participant (Expert 2 is more aware of current BIM-AMs, their importance and their implementation in practice since he is a co-author of the BIM-MM itself).

Secondly, the NBIMS-CMM is built on qualitative measures and could, as a result, be interpreted differently when completed by two different participants who are working on the same project. This was identified by some participants involved in the two projects. For instance, Expert 1 in Project B noted that there is a "need for, simple, plain language questions which can only be interpreted in one way. BIM definitions need to be clearly defined due to the lack of consistency in industry". Similarly, Expert 2 criticised the NBIMS-CMM and described it as a "very subjective" model. Similar observations were found in Chapter 6, Section 6.3 which show how two participants can obtain two different scores applying the same AM to the same project.

In Round 2, Project A, the scores given by Graduates 1 and 2 when completing the NBIMS-CMM show extreme discrepancies (Figure 42, dotted lines: Round 1, solid lines Round 2). Graduate 1 gave an overall score of 92.8, 'Platinum' level of maturity, which is 60 points more than the score given by Graduate 2 (35.7 Non-BIM). According to NIBS (NIBS, 2012), participants have to give a minimum score of 40.1 in order for a project to be considered as applying BIM. This means that the Project A is not considered to be applying BIM according to the assessment completed by Graduate 2 and at the same time gets the highest level of maturity, 'Platinum', from Graduate 1. Far less contrast was identified in Round 1 when the experts completed the AM on the same project.

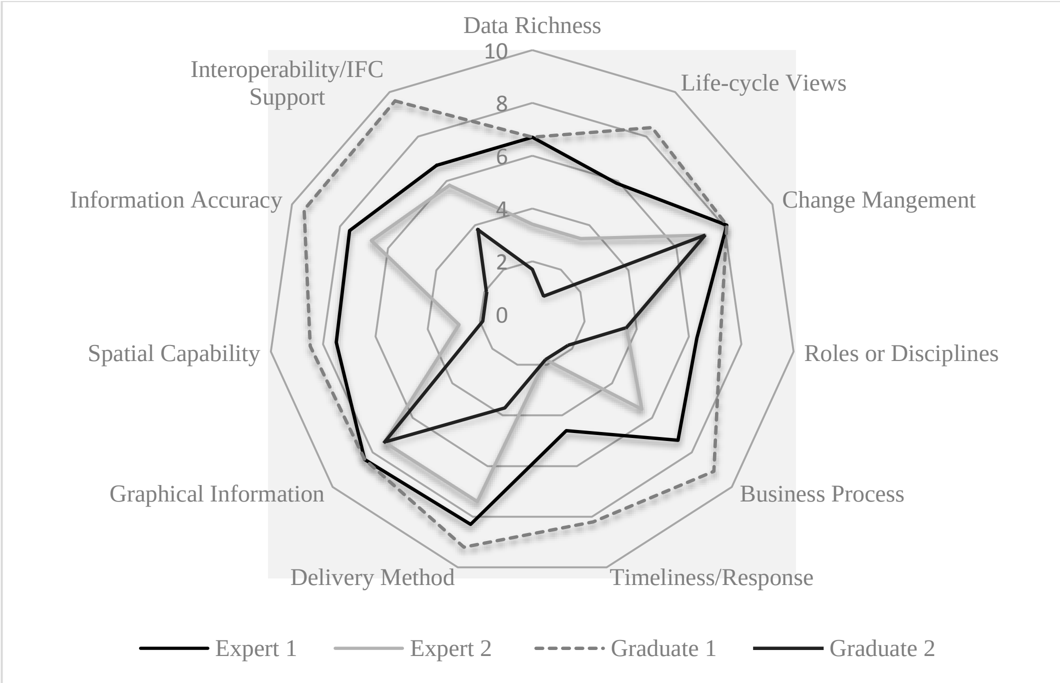


Figure 42 A comparison of scores obtained by the four participants in the two rounds when applying NBIMS-CMM

Differences in scores across the 11 measures are presented in Table 37, which also provides a rank order. None of the eleven measures obtained the same score by Graduates 1 and 2. Even the rank order is completely different. One exception can be found in 'Timeliness/Response' which is eighth in both ranking orders, but also has more than 6 points difference. In addition, similar rank order is reported on Delivery Method and Data Richness, highlighted in light grey.

Table 37 Capability maturity model for the same project with two different participants: Project A

BIM areas of interest	Rank order	Graduate 1	Rank order	Graduate 2	Difference
Interoperability/IFC Support	1	9.6	3	3.8	5.8
Information Accuracy	2	9.5	6	1.9	**7.6**
Delivery Method	3	9.2	4	3.7	5.5
Business Process	4	9.1	8	1.8	7.3
Spatial Capability	5	8.5	7	1.9	6.7
Life-cycle Views	6	8.4	11	0.8	7.6
Graphical Information	6	8.4	1	7.4	1
Timeliness/Response	8	8.2	8	1.8	6.4
Change Management	9	8.1	2	7.2	**0.9**
Roles or Disciplines	10	7.2	5	3.6	3.6
Data Richness	11	6.7	10	1.7	5
Overall Score		92.8 Platinum		35.7 Non-BIM	

The rank order and the overall results are remarkably different from Round 1. Experts, including Experts 1 and 2, give the same rank order in seven measures, compared to only one in Round 2. The experts show more consistency in their results compared to the graduates as seen in the dotted and solid lines in (Figure 42).

7.4.2 Same participant applying two BIM-AMs to the same project

In **Project A, Round 1,** the NBIMS-CMM and the BIM-MM were applied to the same project by Expert 2; the BIM development manager (Figure 39). When completing the NBIMS-CMM, the overall score was 54.8 points, which allocates the project to a 'Minimum BIM' rating, the lowest level of maturity available in NBIMS-CMM. In a second stage, Expert 2 applied the BIM-MM to the same project. The overall score using the BIM-MM was 50% (Arup aims to have their projects with score 50% and above). Unlike the NBIMS-CMM, the overall score is not allocated to a specific level of maturity in BIM-MM and only provides the results as a percentage. **In Project B, Round 1,** similar results are reported as Expert 2 scored 50 points (Minimum BIM) when using the NBIMS-CMM, and 52% when applying the BIM-MM.

In **Project A, Round 2,** the scores by Graduate 2 applying two BIM-AMs are more contrasted than Round 1. When using NBIMS-CMM, the project scored 35.7 points, which is lower than the minimum level of maturity according to the NIBS, and 47% when using the BIM-MM. In **Project B, Round 2**, Graduate 2 showed contrasting scores applying the two AMs with 68 (Certified) applying NBIMS-CMM and 57% in BIM-MM. In both CSP 1 and CSP 2, the overall scores by all participants tend to be more similar when applying the BIM-MM and greatly contrasted when applying the NBIMS-CMM.

7.4.3 Six different participants applying three BIM-AMs to a single project

In each round, three BIM-AMs are applied to the same project. Table 38 shows the scores from the eleven participants and using three AMs on the same project. The findings show that very different outcomes can be achieved when applying different AMs to the same project. In CSP1, for instance, the project is certified as Silver with VDC Scorecard and at the same time is allocated to Minimum BIM when applying the NBIMS-CMM. Direct, numerical comparison of overall scores across multiple AMs is difficult since AMs vary significantly in terms of structure, focus and content.

Table 38 Results of the fifteen completed AMs in the two case study projects

	Project A	**Project B**

	Participants	AM	Score	Participants	AM	Score
Round 1: experts	Expert 1	NBIMS-CMM	77.3 Silver	Expert 1	NBIMS-CMM	49.3 Min-BIM
	Expert 2	NBIMS-CMM	54.8 Min-BIM	Expert 2	NBIMS-CMM	50 Min-BIM
		BIM-MM	50 %		BIM-MM	52%
	Expert 3	VDC Scorecard	54 % Advanced practice	Expert 3	VDC Scorecard	52% Advanced practice
Round 2: graduates	Graduate 1	NBIMS-CMM	92.8 Platinum	Graduate 1	Could not take part	
	Graduate 2	NBIMS-CMM	35.7 Non-BIM	Graduate 2	NBIMS-CMM	68 Certified
		BIM-MM	47%		BIM-MM	57%
	Graduate 3	VDC Scorecard	35% Typical practice	Graduate 3	VDC Scorecard	40% Typical practice

7.4.4 Which AM to trust?

This testing shows contrasting scores when applying three different AMs to the same project. A project can be allocated the lowest maturity level by one assessment and the highest by another. Rather than arguing which AM to trust, the AEC industry has to use these models intelligently and understand that each has its advantages and disadvantages. The following discusses the consistency of results which is critical to the credibility of AMs.

A critical point when applying BIM-AMs is whether individuals completing the AMs answer the BIM questions differently. It has been seen that two different people applying the same assessment to the same project can provide different answers, even if the relative scores are similar. This is due to issues related to the subjectivity of the AMs and the standards of writing in these assessments that needs to be improved . Evidence can be found in 10 instances across the two projects when comparing the results of two different participants applying the same AM to the same project. This limitation has also been found in a previous study carried out by CIFE researchers who applied the VDC Scorecard. When describing the limitations of their study, Kam et al. (2013b) indicated that the main challenges of the scorecard were concerned with its qualitative measures. They explained:

> Interviewer/scorer interpretations are subjective. Interviewers, particularly inexperienced ones, can come to significantly different results even when they are looking at the same data for the same project. The measures pertaining to the contents covered by the BIM Execution Plan (BEP)/VDC guides, project management system features, number of stakeholders incentivized to use BIM, and the model uses have the greatest variations between experienced and inexperienced users. Many of these student evaluators did not have prior experience with BIM and thus, had greater difficulty interpreting some concepts such as the maturities of model uses. Ongoing work includes training interviewers to standardize the interview process and creating a comprehensive scorecard manual that defines all terms, measures and inputs.

Consistency levels, however, vary across different AMs. When applying the NBIMS-CMM deficiencies between the experts and graduates are significant in the two CSPs. Amongst the six completed NBIMS-CMMs in CSP1 Round 1 and 2, and CSP 2 Round 1, only two identical answers were reported between Experts 1 and 2. This is mainly related to the subjectivity of NBIMS-CMM, a problem that is reported by the model's developers themselves who note (NIBS, 2007):

> Since the words are subjective and open to interpretation, it is likely that no two people will always agree on all the possible divisions or descriptions of the varying level of maturity

Subjectivity should be one of the main challenges that needs to be addressed in the field of BIM-AMs. Creating an automate model that creates accurate and objective data might be the key for optimising the current BIM-AMs.

In contrast to NBIMS-CMM, the BIM-MM provides more common answers between experts and graduates. This can be seen in Table 39 where Expert 2 and Graduate 2 in Project A provided the same scores to more than half of the measures (highlighted in grey). Similarly, in Project B, Expert 2 and Graduate 2 provided the same answers to nearly half of the measures. In addition, both projects have some common areas. In the BIM Champion section, all four participants report the same score, 2 points (level 2 Managed), which means that BIM Champion with adequate time commitments is guiding teams in these projects. This can also be seen in two other measures, BEP (level 4 Measured: project BEP exits for all parties, and based on EIRs) and Open Standards (Level 2 Managed: successful export/re-import of IFC/COBie verified at each issue). The high levels of consistency of the BIM-MM in comparison to the inconsistencies when applying the NBIMS-CMM might be related to the features of the model in terms of clarity and structure and the previous experience of the assessors. In NBIMS-CMM, each of the eleven measures has ten possible increasing levels of maturity, whilst in most AMs in the literature (Chapters 3 and 5) maturity models are more focused, with only five to six maturity levels.

Table 39 Consistency of BIM-MM across the two CSPs

Project measures	Project A		Project B	
	Expert 2	Graduate 2	Expert 2	Graduate 2
EIRs	0.80	0.80	0.80	3.20
BIM Data Review	0.90	0.90	0.90	2.70
BEP	3.60	3.60	3.60	3.60
Procurement	0.80	0.00	2.40	3.20
CDE	1.00	3.00	1.00	3.00
Version, Status	4.00	5.00	3.00	4.00
Marketing Strategy	0.00	1.20	0.00	0.00
VDRs	4.00	4.00	4.00	3.00
Open Standards	1.80	1.80	1.80	1.80
BIM Contract	0.00	1.80	1.80	1.80
BIM Champion	2.00	2.00	2.00	2.00
Overall Score	50%	47%	52%	57%

7.5 Discussion and conclusion

In the still-developing field of BIM-AMs, there are many opportunities, but also more challenges remain. Practical and theoretical issues, such as, the reliability, validity, consistency and accuracy of these assessments must be addressed. From the literature review, sixteen AMs were identified in Chapter 3, and have been compared and analysed in Chapter 5. Experimentally, two of them were examined in Chapter 6 and broader and more comprehensive testing of three of them was applied in Chapter 7.

BIM-AMs applied in this thesis evaluate the maturity levels of BIM across projects. However, it has been seen that the outcomes of the AMs' are different according to assessors' levels of experience and knowledge, and therefore, companies can develop and use AMs to assess individuals’ experiences of BIM. This would help managers to exchange experiences, as Andrew Duncan notes (CIBSE, 2015):

> ‘We might have one discipline doing more BIM than another, and so we will recycle experience from a mature team into one with less BIM knowledge’.

In the reviewed literature of BIM and non-BIM domains, in addition to the results reported in the tests undertaken in Chapter 6 and 7, it has been observed that consistency is still one of the substantial challenges of AMs, since most rely on qualitative measures. In order to address this challenge, automation might be a new emerging direction for AMs, which provides a robust and consistent approach of BIM performance measurement (see Chapter 8). It has also been found that BIM-MM provides more consistent results than the other two applied models. This might be linked to the AM’s design, but could also be due to consistent training provided internally at the company involved in this study.

The use of BIM-AMs to enhance dialogue

The conflicting scores of BIM-AMs between experts and graduates perhaps shows the knowledge boundaries across different levels within the organisation; a challenge that has been reported in previous research that focuses on transforming knowledge across boundaries in other fields (de Haas & Kleingeld, 1999; Dossick & Neff, 2010; Neff et al., 2010). In order to bridge these divisions, it is crucial to highlight the role of AMs as frameworks that help organisations focus their priorities and communicate them internally within the business and externally with other engaged stakeholders.

As discussed in Section 3.9, Cole (2006) explained how AMs in the building environmental domain are being used as a “common language” by different project disciplines, and how this can encourage a dialogue throughout an organisation. This has also been emphasised by the developers of the recognised Balanced Scorecard, who explain that their model is a “top-down reflection of the company’s mission and strategy”. They add that their scorecard is beneficial in “communicating priorities to managers, employees, investors [and], even customers”. Although such benefits and roles have not been documented yet in the BIM research field, it has been seen from this research that assessments can be used to enhance dialogue between the different parties engaged in the project. As Interviewee 9 (Section 4.1.4, a BIM development manager) explains:

> ‘I think it is only through measuring ourselves we will be able to honestly present that data that we really start a conversation, what is BIM to our client and how do they get the most value out of it.’

As Andrew Duncan of Arup highlight (CIBSE, 2015):

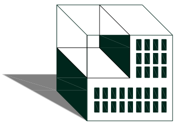
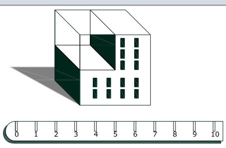
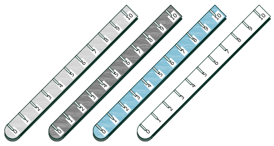
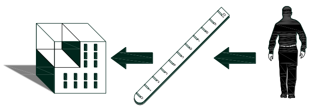
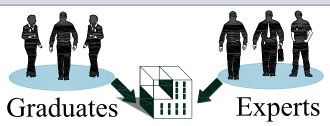
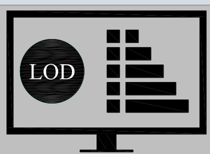
> ‘It’s a way of tracking our internal processes and of starting a conversation with different parts of the construction industry to see what BIM means to them.’

In the building environmental AMs, Schweber (2013) discussed the potential of BREEAM, (Section 3.4.1), to introduce professionals to a wide range of sustainability measures outside of their domain expertise. According to her, BREEAM, with its combination of “radically different types of elements and associated measures”, can transfer complexity of ‘green building’ into a single core. Similarly, in the series of tests undertaken in this chapter, participants were introduced to some measures that they were unaware of, or unable to answer, since they were not involved with them. They, therefore, had to contact other project members for further information to complete the assessment.

Accordingly, BIM-AMs, by grouping the BIM criteria into a structured fashion, can be used not only to evaluate the implementation of BIM, but also as a framework to provide professionals with a clear message on the most critical features of ‘BIM’. This will help different stakeholders, including policy-makers, researchers, professionals and clients, to understand what counts as BIM and create a greater dialogue, which becomes an integral part of the decision process within the AEC businesses.

8 Automated BIM-AM: Development and testing of a new approach

In Chapters 5, 6, and 7, it has been observed that subjectivity is one of the fundamental limitations of current BIM-AMs. In order to overcome this problem, Chapter 8 sets out a proposal for a new approach to the evaluation of BIM, namely, automation.

1: Introduction	**2: PMSs**	**3: BIM-AMs**
		
Main questions included: What is BIM? What is the need for BIM-AMs?	Includes: - Brief history of the broad PMSs, their definitions - PMSs roles and barriers - Sample of PMSs	- Explains the wide range of BIM-AMs, their evolution, opportunities and challenges - Investigates how BIM-AMs have been informed by the broader PMSs
4: Research methodology	**5: Perspectives on BIM-AMs**	**6: Pilot Testing**
		
Introducing the chosen research methods including questionnaire, interview and the implementation of multiple AMs in practice	- Critical analysis of the BIM-AM, their similarities and differences - This includes the design process, the complexity and the range of measures	Initial testing of individual and multiple AMs in practice in association with a number of practices
7: Comprehensive testing	**8: Automated BIM-AM**	**9: Conclusions**
		
In association with Arup, applying three AMs to the same project and completed by six participants who have different BIM experience i.e. experts and graduates	Includes: - The need for automated AMs - The implementations of BIM-AM in practice	Current perspectives and future directions of BIM-AMs

8.1 Why automate the BIM-AM?

The approach commonly taken in the current literature of BIM performance measurement relies on manual assessments that contain subjective measures. None of the existing AMs, however, is designed to automate the process of assessment, which has the potential to provide information rich, quick and accurate evaluation of BIM performance. This section sets out the need for automation based on the literature of performance measurement in general and, BIM in particular, coupled with the findings of the tests undertaken in Chapters 6 and 7.

8.2 Observations from the performance measurement literature

Neely et al. (1997) identified a list of desirable criteria for performance measures, as discussed in Section 2.6. They concluded that measures have to be consistent, objective, exact, precise, enable quick feedback and use, whenever possible, data that are automatically collected. These critical characteristics have been difficult to achieve with classic and traditional methods. Paper-based AMs have been criticised for being labour intensive, too slow, cumbersome and unreliable (Sharman & Kavan, 1999). Navon (2007) explains the deficiencies of manual data collection. Current practice of construction project performance control is labor intensive since it is based on manual data collection that requires extractions from different resources including plans (budget, schedule), drawings and databases. The manually collected and extracted data are error prone, expensive and might suffer from low quality. Therefore, projects might be assessed and controlled infrequently. Automation, has been seen as a solution and a necessity to overcome issues of accuracy and consistency. Marr and Neely (2003) explain the need:

> "Alison Classe (1999) notes that paper and pencil, or simple spreadsheet tools are everything you need to start applying a balanced scorecard, but if you decide to make the method an integral part of the business, automation will usually be necessary"

As a result, new frameworks have emerged in an attempt to automate the process of performance measurement in different research fields, including business management and building environmental AMs. For instance, various software vendors have developed platforms that automate the Balanced Scorecard (Section 2.3.1) which have three main advantages, namely, integrating data from different resources, enabling overarching data analysis, and assisting organisations in widely communicating the results (Marr & Neely, 2003). This has also been observed in the built environment domain where research has been focused on converting standard AMs, such as BREEAM, into automated models.

This is exemplified in the work undertaken by researchers at Cardiff University who have developed an automated sustainability compliance checking. Their work involved translating the manually maintained models (parts of BREEAM) into an automated rule engine that assesses the building model (Beach et al., 2013).

8.3 Observations from the BIM-AM literature

In the BIM literature, most current AMs have been criticised for their dependency on qualitative and subjective measures that rely on assessors' opinions. Researchers have argued that "subjective measures are sometimes un-reliable and difficult to interpret and understand" (Kam et al., 2013b). They explained that a well-designed AM should be consistent, accurate (Succar et al., 2012) and built on objective and quantifiable measures (Kam, 2013). The relatively recent frameworks, such as the VDC Scorecard, have attempted to address these issues by applying quantitative measures. As Kam (2015) notes:

> "If the building industry is to unlock the potential of BIM, it must apply objective, repeatable, reliable metrics and learn how to extend successful approaches across project portfolios. The methodologies must include reliable evaluation and quantitative measures of performance to help organisations optimise the business decision making, processes and technologies that are used to support the cycle of the built environment"

Despite this acknowledgement of the need for quantitative measures, the VDC Scorecard is a human processed model that leaves immense room for assessors to "guess" answers of the measures evaluated. This problem has been identified by the developers of the VDC Scorecard who explained that assessors can give different outcomes when evaluating the same project. They have, therefore, asked assessors to score their 'confidence level' to indicate the accuracy of each answer (0-100%). However, when applying the VDC Scorecard to 108 projects, the confidence levels were low, with 'a mean value of only 33%' (Kam et al., 2013b), which raises questions about the validity and reliability of the outcomes.

To overcome challenges of inconsistency and accuracy, the research field of BIM-AMs should focus on automation. An automated AM is seen to provide professionals with a new effective approach, which replaces traditional assessments with rapid and consistent measures. This chapter introduces an approach that automates the evaluation of BIM. It focuses on one measure, the Level of Detail (LOD), which is the most documented measure across the sixteen current BIM-AMs, as discussed in Section 5.4.

In order to evaluate the LOD of model objects, a Revit plug-in was developed by the research team and then applied to multiple projects in association with two AEC companies. The following provides a background on the LOD definitions and the ways it has been evaluated in previous studies.

8.4 Level of Detail

LOD is 'the maximum amount of information and geometry authorised for use by others'. It refers to the geometrical and non-geometrical information which an organisation needs to complete a specific task when implementing a BIM project within a certain timeframe (Harvard University Construction Management Council, n.d.). In the wide research field of BIM, LOD has been the subject of considerable research, with multiple perspectives and interpretations (Bedrick, 2008; Eastman et al., 2009; Leite et al., 2011).

The first and most widely-accepted document that provides definitions of LOD is the E202 LOD standard, initially developed in 2008 by the American Institute of Architects (AIA) (AIA, 2008). At different stages of a project's life-cycle, professionals can use the AIA standard to allocate model objects to one out of five LODs, namely, 100, 200, 300, 400 or 500. These increasing levels reflect the increasing richness of information attached to every object in the model, which ranges from having basic information in LOD 100, such as volume, location, area and height, to more detailed data in LOD 500, where model elements include accurate geometrical information (size, shape, orientation and quantity) and non-geometrical information (such as, time and cost).

The evolving interest in LOD has led to many different studies that attempt to standardise and classify the LOD of project objects into different levels. Such attempts have generally been based on the AIA standard. In the UK, for instance, 'The Level of Development Specification' adopts same five levels of AIA standards. Its developers, the BIMForum working group, have only added another level LOD 350, which builds upon LOD 300. Another study by Leite et al. (2011) have built on the LODs suggested by software vendor which suggest three classifications for LOD, namely, approximate geometry (generic elements without defining their specific properties), precise geometry (elements that have materials and detailed properties) and fabrication (elements have details of assemblies as they appear in shop drawings).

The AIA LOD classifications are presented in Table 40, along with the LOD classification identified by other three studies.

Table 40 Different perspectives on LOD

LOD	(AIA, 2008)	(Harvard UCMC, 2013)	(Leite et al., 2011)	(Kam et al., 2013a)
LOD 100	The Model Element may be graphically represented in the Model with a symbol or other generic representation, but does not satisfy the requirements for LOD 200. Information related to the Model Element (i.e. cost per square foot, tonnage of HVAC, etc.) can be derived from other Model Elements.	Estimate it		Conceptual
LOD 200	The Model Element is graphically represented within the Model as a generic system, object, or assembly with approximate quantities, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element.	Specify it	Approximate geometry: equivalent to LOD 200	Approximate geometry
LOD 300	The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of quantity, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element.	Purchase it	Precise geometry: equivalent to LOD 300	Precise geometry
LOD 400	The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of size, shape, location, quantity, and orientation with detailing, fabrication, assembly, and installation information. Non-graphic information may also be attached to the Model Element.	Build/ Install it	Fabrication: equivalent to LOD 400	Fabrication
LOD 500	The Model Element is a field verified representation in terms of size, shape, location, quantity, and orientation. Non-graphic information may also be attached to the Model Elements.	Operate it		As-built

8.5 LOD definitions in the BIM-AMs literature

LOD is a critical criteria to consider when implementing BIM (Leite et al., 2011). It is evaluated in seven of existing BIM-AMs including the NBIMS-CMM, VDC Scorecard and BIM-MM. The developers of these AMs, however, have interpreted the LOD differently and used different terminology, namely, level of detail, level of development, or data richness. These terms are sometimes used interchangeably.

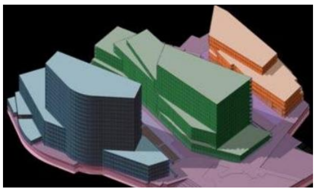
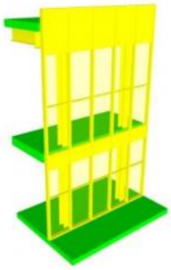
LOD was first evaluated in NBIMS-CMM in 2007, expressed as Data Richness (NIBS, 2007). The NIBS identified LOD as the completeness of the building information model. It is assessed against ten increasing maturity levels ranging from level 1, where the model is developed but has very limited data attached, to level 10 where data is transformed to information. In level 10, information is reliable, valuable, useful, authoritative and extracted from the model. Measuring the LOD of elements according to NIBS does not include assessing whether the elements are 2D, 3D, 4D or 5D since these dimensions are evaluated in another measure; Graphical Information.

In the BIM-MM, LOD represents how developed model elements are which in addition convey to other participants, via a BIM Execution Plan, what these elements can be used for (Arup, 2014). Most measures in the BIM-MM have six different possible answers, the LOD, however, has four options:

- 0 Non-Existent: NO LODs considered
- 2 Managed: Consistent LODs for some similar elements
- 4 Measured: Consistent LODs for most similar elements, aligned with BIM Execution Plan
- 5 Optimising: All elements in model comply with stated LODs in BEP

In the BIM measurement literature, LOD has been evaluated based on different criteria; each developer has created different judgement on how to measure the richness of information in model elements. In NBIMS-CMM and BIM-MM, the elements are evaluated generally according to how developed the model elements are. In the AIA standard, LOD reflects the graphical (2D and 3D) and non-graphical information (4D and 5D) attached to each element. What is common, however, across current AMs is the way of assessing. In all models, LOD has been assessed by the judgement of assessors to provide an overall opinion of the model's LOD. An example of the LOD of an element in the AIA is presented in Table 41.

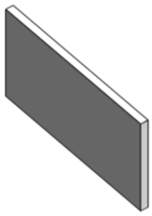
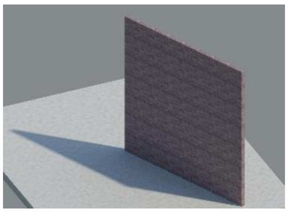
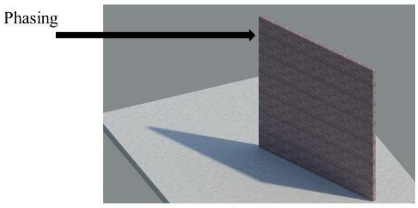
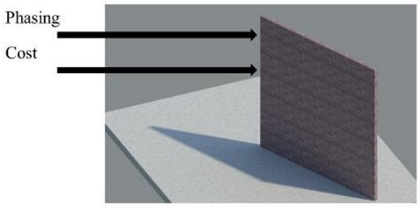
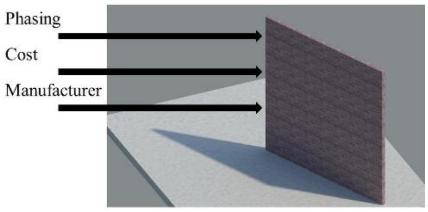
Table 41 LOD of a wall (BIM Forum, 2015)

LOD	Description	
100	Solid mass model representing overall building volume; or, schematic wall elements that are not distinguishable by type or material. Assembly depth/thickness and locations still flexible	
200	Generic wall objects separated by type of material (e.g. brick wall vs. terracotta). Approximate overall wall thickness represented by a single assembly. Layouts and locations still flexible	
300	Composite model assembly with specific overall thickness that accounts for veneer, structure, insulation, air space, and interior skin specified for the wall system. (Refer to LOD 350 and LOD 400 for individually modelled elements). Penetrations are modelled to nominal dimensions for major wall openings such as windows, doors, and large mechanical elements. Required non-graphic information associated with model elements includes: • Wall type • Materials	
350	A composite wall assembly may be considered for LOD 350 only if hosted objects such as windows and doors are provided at a minimum of LOD 350. Main structural members such as headers and jambs at openings are modelled within the composite assembly.	

8.6 Towards the automation of BIM measurement

Several studies have been carried out to evaluate the LOD of BIM models but the main challenge of these studies is the subjective process of evaluation. It is suggested in this thesis that automating the process of evaluation has the potential to solve the problem of subjectivity of existing AMs. In order to automatically assess the LOD of model elements in a quick and subjective manner, a plug-in has been developed for Revit, which measures the amount of information attached to model elements. For each element, the plug-in checks five types of information and allocates one of five LOD categories, 100, 200, 300, 400 and 500, as presented in Table 42.

Table 42 LODs checked by the developed plug-in

LOD	Data checked	Example
LOD 100	Geometry Elements of the model have geometry attached to them	
LOD 200	Material is added: in this level the BIM element has material attached	
LOD 300	Phasing is added: in this level the BIM element has material and phase attached	
LOD 400	Cost is added: in this level the BIM element has material, phase and cost attached	
LOD 500	Manufacturer is added: in this level the BIM element has material, phase, cost and manufacturer attached	

It is important to note that the boundaries between the different LODs in the AIA standard are not very clear. In this thesis, the LODs represent five evolving stages that reflect the information attached to the model, and are suitable for automation. This is illustrated in the flowchart below which represents the process of assessing the LOD of each Revit object. It shows the evolutionary levels that range from LOD 0, where there is no geometry attached to the element, to LOD 500 where the element has geometry, material, phasing, cost and manufacturer attached.

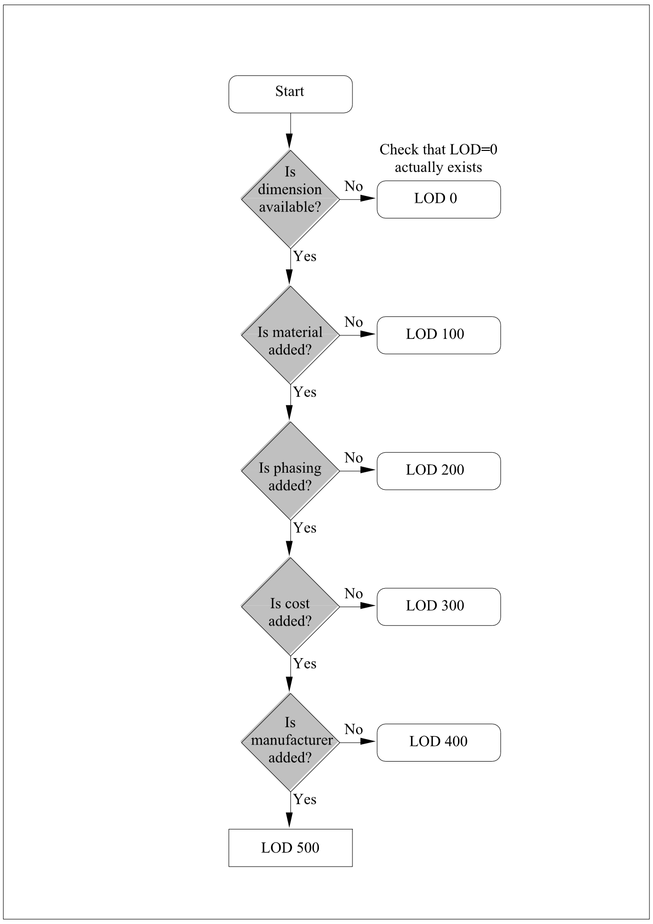


Figure 43 The flowchart of evaluating the LOD by the developed plug-in

To validate the plug-in, a series of tests was carried out on manually created Revit models containing a single element of known LOD. It was observed that when a model element in Revit, such as duct, has no material, the element is allocated LOD 100. A default wall in Revit is allocated LOD 300, which means that the wall has geometry, material and phasing attached to it. If the cost is added manually to the wall, the plug-in allocates the element to LOD 400. Similarly, if cost and manufacturer are added to the wall, then a LOD 500 is reported. It seems to be a feature of the built-in elements in Revit that none of the default Revit objects will have phase but no material.

8.7 Phase 1: Applying the automated BIM-AM to multiple projects

Initial testing of the plug-in was carried out in association with a construction company in Denmark. The company agreed to apply the plug-in to a sample of projects from different project disciplines including structural, mechanical and electrical models. For confidentiality reasons, the company applied the plug-in internally rather than sharing the models with the author. Once projects were tested by the company, the plug-in output files were shared with the author. A total of fifteen projects were tested, some included only one discipline, whilst others included multiple project disciplines.

Evaluating the LOD of the fifteen projects provides a view of how much information is attached to each element across projects, which in turn reflects the overall LOD of each model. Table 43 presents the various LODs reported in each model (although some of these models include very few elements allocated to high levels of detail). It is important to note that Table 43 presents the 'total' outcome of each model, which may contain more than one project discipline. LOD varies within the same model and across project disciplines. For instance, in Project 10, an architecture model, 93% of the elements are LOD 100, 5% to LOD 300, 1% to LOD 400 and 1% to LOD 500. This is significantly different in the mechanical and electrical models of Project 10, where all model elements are LOD 100.

Table 43 model elements distribution across LODs and number of elements in each LOD

	LOD 100 Geometry	**LOD 200 Material**	**LOD 300 Phase**	**LOD 400 Cost**	**LOD 500 Manufacturer**
Project 1	34940		1314		
Project 2	20267		1546		
Project 3	11548		427		
Project 4	27769		1569		
Project 5	30415		1741		
Project 6	10033				
Project 7	65344		1801		
Project 8	8124				
Project 9	29346		1353		
Project 10	190972		9964	1172	1751
Project 11	9943				
Project 12	119688		3534		
Project 13	2254		1538		106
Project 14	81218		10422		1456
Project 15	29890		1178		

As seen in Table 43, three projects are allocated to LOD 100 and have no model elements that have more than geometry attached to them, twelve projects contain elements that have not only geometry, but also material and phasing (LOD 300). Furthermore, only three projects have elements that include geometry, material, phase, cost and manufacturer (LOD 500). However, none of the projects include elements allocated to LOD 200 or 400 and only Project 10 has some elements allocated to LOD 400.

8.7.1 LOD across mechanical and electrical models

LOD varies across different disciplines as seen above. Some project disciplines have elements of high LOD and other disciplines have all their elements allocated to one low LOD. The most common project disciplines across all evaluated projects are mechanical and electrical models that are evaluated in twelve and five models respectively. Observations of the LOD across these two disciplines show that all model elements of electrical and mechanical models are allocated to LOD 100. In other words, none of the model elements include both geometry and material. The only difference noted across these projects is the number of model elements which peaks in Project 12.

8.7.2 The outcomes of the AM in one CSP

In order to illustrate the outcomes of the automated plug-in on one project, results of Project 1 are presented in this section, which is valuable to illustrate the LOD of one project across different disciplines. In Project 1, the AM was applied to five different models, namely, existing building, mechanical, structural, electrical and new building models. As seen in Figure 44, none of the elements included in the five tested models is allocated to LOD 200, LOD 400 or LOD 500.

Most elements fall under LOD 100 whilst only three models have LOD 300 elements; existing building, structural and new building models. This means that elements in Project 1 have either geometry attached to them or geometry, materials and phase. Interestingly, the existing building model include a high percentage of LOD 300 elements (86% of its elements) compared to only 14% allocated to LOD 100. In contrast, the structural model has a very small number of LOD 300 elements (1%).

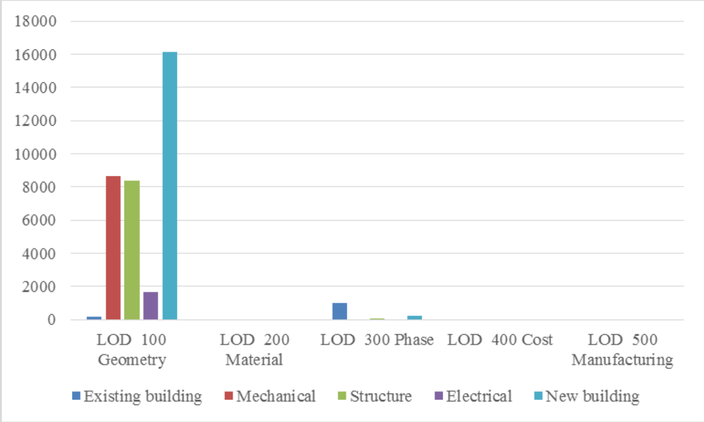


Figure 44 LOD of five models in Project 1

The testing undertaken in Phase 1 offers an example of how an automated BIM-AM can be applied to a range of projects. Through the use of this AM, professionals can measure the current LOD of their model elements and improve these models accordingly. Based on the findings of the fifteen projects, it could be said that models in practice have different LODs since each BIM element might have a unique desired LOD. Determining the LOD of elements is often influenced by different issues, including the project discipline, the BIM model use and project stage. BIM use in this company seems to follow similar trends across multiple projects. This is evidenced in electrical and mechanical models, where all their elements are allocated to the lowest LOD. However, to understand how LOD changes across project stages, the following section presents the application of the plug-in to one project across three development stages.

8.8 Phase 2: Applying the automated BIM-AM to one project across three stages

The testing carried out in Phase 2 was undertaken in association with an international, UK-based consultancy engineering company. The company agreed to take part in this research after the UK Regional Lead of the company was contacted. There were two main challenges to apply the plug-in in the company; client confidentiality and IT security. The company suggested three case studies but due to client confidentiality, they were only able to share one project but at different stages of the project life-cycle (this has not tested in Phase 1). In terms of IT security, the BIM Lead explained that as a business they could not install an unknown plug-in in their offices since there was ‘too much risk involved’. Usually, the IT services of the company only installs a plug-in after being thoroughly tested and they did not have the resources available to do so at the time. It was therefore agreed that the models would be sent to the author for testing, which required a Non-Disclosure Agreement between the company, the author and the University of Bath.

In Phase 2, the CSP did not only include the application of the BIM-AMs to the BIM models (as in Phase 1) but also requested the BIM Lead to evaluate LOD based on his personal judgement. This was important to compare the automated approach versus the human judgement of the LOD.

The CSP is located in the Middle East, and the BIM Lead chose this particular project since it offered a great example of progression across three development stages. The development of the BIM model in this project did not follow the RIBA Plan of Work stages (Figure 45), which is often followed in this company's projects located in the UK. Instead, similar stages were implemented as alternative to RIBA's stages. These stages are 30% (alternative to RIBA Stage 2 Concept Design), 60% (alternative to Stage 3 Developed Design) and 90% (alternative to Stage 4 Technical Design). The BIM Lead shared Revit models at these three stages. Each model file included five separate sub-models that reflect project's disciplines; structural, mechanical, electrical, public health and fire models, resulting in 15 Revit files overall.

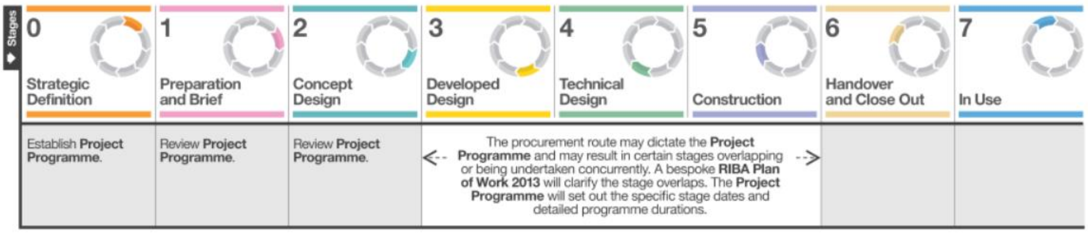


Figure 45 RIBA plan of work

The findings show that number of elements in all models increase as the project evolves. In the three structural models (Figure 46), number of the elements increases when the project stage develops. For instance, number of elements at stage 90%, with LOD 100, is over twice the number of model elements at stage 30%, and the number of elements at stage 90%, with LOD 300, is almost three times the number of elements in stage 30%.

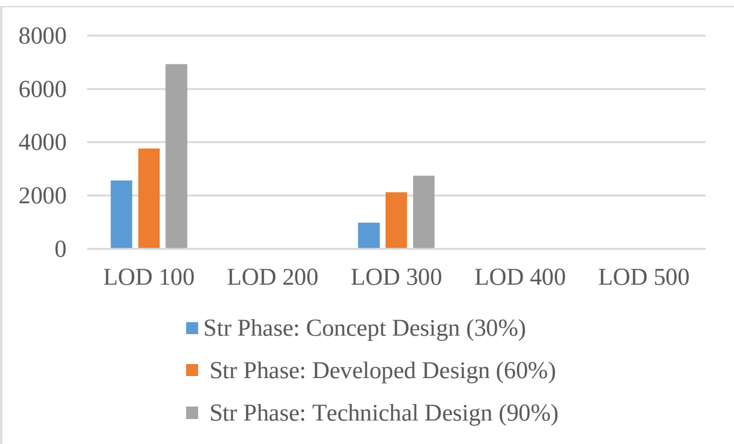


Figure 46 Structural model across three project stages

Through the use of the plug-in, the LOD of each element of BIM models can be identified. In structural models, and throughout the three project stages, model elements are allocated to either LOD 100 or LOD 300. In Developed Design Stage, 64% of model elements are assigned to LOD 100 compared to 36% to LOD 300. This means that more than quarter of the BIM elements of structural models have not only geometry attached to them, but also material and phasing. This is also observed in other stages of structural models. In Technical Design Stage 72% of elements are classified as LOD 100 compared to 28% allocated to LOD 300.

The rest of the project disciplines are similar to structural models in regard to the gradual increase in number of elements as the project evolves (Figure 47 and Figure 48). Nevertheless, this increase differs in its LOD and seems to be less significant in Fire and PH models compared to the other disciplines. However, mechanical, electrical, PH and fire models are different from structural ones in terms of elements' LOD. In all twelve models, elements across the three stages of the project, are allocated to LOD 100, which means that none of these elements has materials attached.

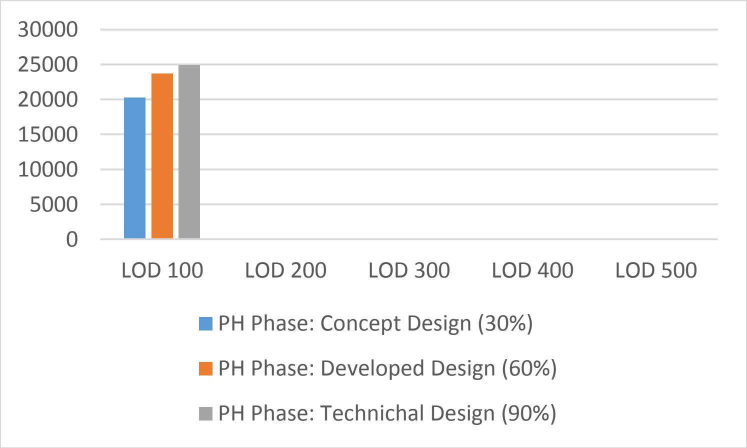


Figure 47 PH model across three project stages

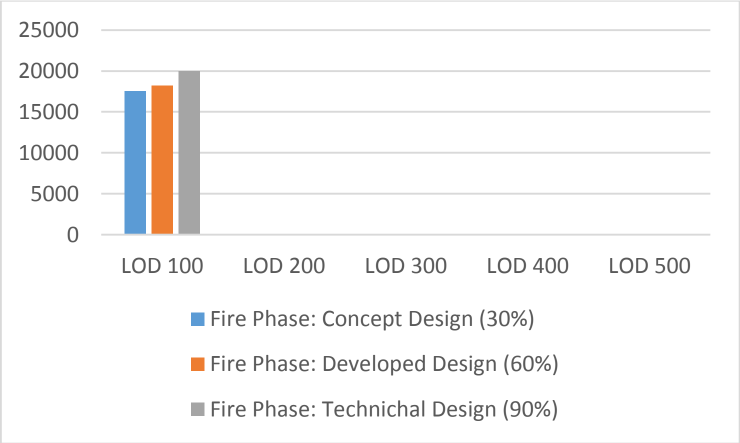


Figure 48 Fire model across three project stages

8.8.1 Automation versus human judgement

In parallel with the testing of the automated BIM-AM, the UK Regional BIM Lead of the company was contacted to evaluate the LOD of the models based on their own judgement as would be the case with a non-automated AM. To assist with this, a simplified version of the AIA LOD description was sent to him, as shown in Table 44. The aim was to compare the human judgement of LOD against the outcomes of the plug-in.

Table 44 LOD descriptions sent to the company

LOD	Description
LOD 100	The Model Element may be graphically represented in the Model with a symbol or other generic representation, but does not satisfy the requirements for LOD 200. Information related to the Model Element (i.e. cost per square foot, tonnage of HVAC, etc.) can be derived from other Model Elements.
LOD 200	The Model Element is graphically represented within the Model as a generic system, object, or assembly with approximate quantities, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element.
LOD 300	The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of quantity, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element.
LOD 400	The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of size, shape, location, quantity, and orientation with detailing, fabrication, assembly, and installation information. Non-graphic information may also be attached to the Model Element.
LOD 500	The Model Element is a field verified representation in terms of size, shape, location, quantity, and orientation. Non-graphic information may also be attached to the Model Elements.

The BIM Lead explained that LOD changes across a project's life cycle. As a project progresses, LOD is expected to increase. The BIM Lead noted:

> "Structural models in terms of LOD tend to start at LOD 3 at 30% (Stage 2) and progress to LOD 4 at 60% (Stage 3), we don't go beyond LOD 4. It's odd, as in the NBS Specification some concrete elements require Reinforced Concrete (RC) details to be modelled at LOD 4 and others don't. In general we wouldn't model RC at any stage (unless a complex arrangement), it would almost all be in 2D or data only."

This does not match with the outcomes of the automated assessment (Figure 46 and Figure 49). When comparing the LOD of the structural models, it was seen that LOD 300 (geometry, material and phasing) has increased by 8% in the Developed Design when compared to the Concept Design model. However, what is surprising is that structural models in Technical Design and the Concept Design stages have exactly the same proportion of elements allocated to LOD 100 and LOD 300. In other words, there is a drop in the overall proportion of model elements allocated to LOD 300 in the Technical design stage compared to the Developed

Design stage. An observation might be that more LOD100 elements are added to the model in Technical Design stage that do not require a higher LOD.

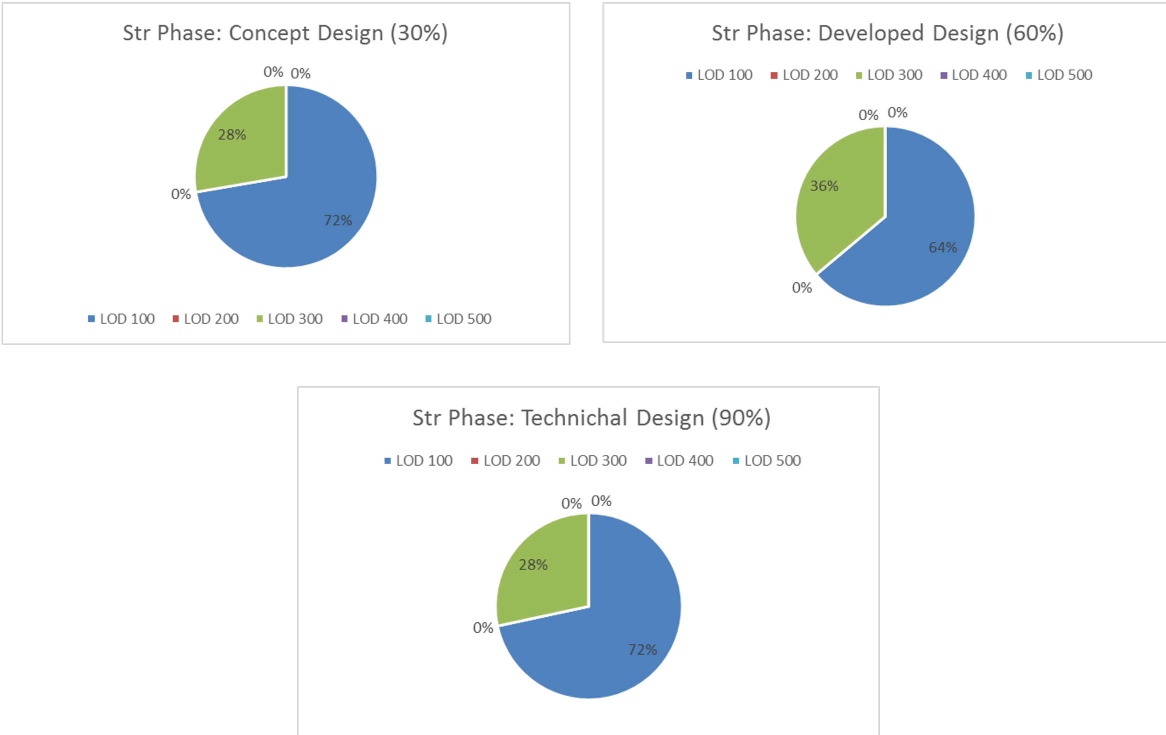


Figure 49 LOD progression across project stages in structural models

The BIM Lead also explained that less progress is made in MEP models. He said "MEP models progress from one to three in alignment with RIBA stages, but then stop at 3 as we would not normally select final equipment, a contractor would do this." The BIM Lead added that it is "difficult to describe an overall model as one LOD/Level of Information (LOI) or another, it is much more complex than that". This is in line with what is observed in the literature where researchers note that LOD is based on individual objects rather than models (Harvard University Construction Management Council, n.d.). Furthermore, to illustrate how LOD is determined in the company, the BIM Lead shared with the author their own in-house standard LOD Delivery Table. The table is based on the BIMForum LOD Specification that adopts same LODs as the AIA standards, discussed in Section 8.4. The company's LOD standard lists the desired LOD at each stage of a project for each object (such as, walls, beams, cables, and railings) and provides a section for description/comments for each element. The document is sometimes used by the company as part of contractual agreements and is usually completed by the BIM Lead. Observations of the standard show that none of the model elements are required to be modelled to LOD 400 or LOD 500.

What is interesting in this standard is that some of the elements are kept as LOD 100 across all the project stages without the need to reach higher levels of detail later in the project. In addition, other elements are not required to be in the model at the early stages of the project, but rather, they are recommended to be added at later stages (such as most of the electrical elements). For instance, some elements are added only at Stage 4 of the project, and might be LOD 100. Adding elements with low LOD at late stages of a project's life-cycle is the cause of the drop in the proportion of high LOD elements in the structural model in the Technical Design stage (Figure 49).

Another way to approach Phase 2 is to organise data according to a project's phase. By doing so, a comparison of LOD can be made across project disciplines at the same phase. For instance, as seen in Figure 50 at Concept Stage, structural models are the only project discipline that contain some LOD 300 elements, and it is also the discipline that has the lowest number of model elements. Same observations are also reported across the other two stages of the project (Figure 51 and Figure 52). In contrast to structural model, mechanical model includes the highest number of elements in Concept Design stage and in Developed Design stage, but it is replaced by electrical models in the Technical Design stage.

Currently in the AEC industry, companies are following different approaches to determine the required LOD at each phase of the project. Some build on the American standards that have been later adopted by the BIMForum in the UK. In the BIM literature, several researchers and professionals have offered their own recommendations for the desired LOD at each stage of a project (Arup, 2014; Harvard University Construction Management Council, n.d.; Kam et al., 2013a). However, checking the LOD of model elements is still subjective. As the BIM Development manager noted:

> At the moment [deciding the LOD of an element] is very very subjective…. But generally speaking, we will model LOD 100, LOD 300. Or we will call something that could be interpreted as 300 LOD, 200, because if you look at the differences between the definitions they are not very clear.

In the tested project, the interpretation of the BIM Lead is different from the company's standard he shared with the author. According to him, some elements should reach LOD 400, whereas in the LOD standard they implement, none of the elements are supposed to reach more than LOD 300. Despite the guidelines offered by professional and academic communities, measuring LOD in practice is still challenging with the traditional methods of evaluation. This study has shown that automation enables an accurate evaluation of LOD of all the elements of the model. This reflects an overall image of how much information is embedded in the model.

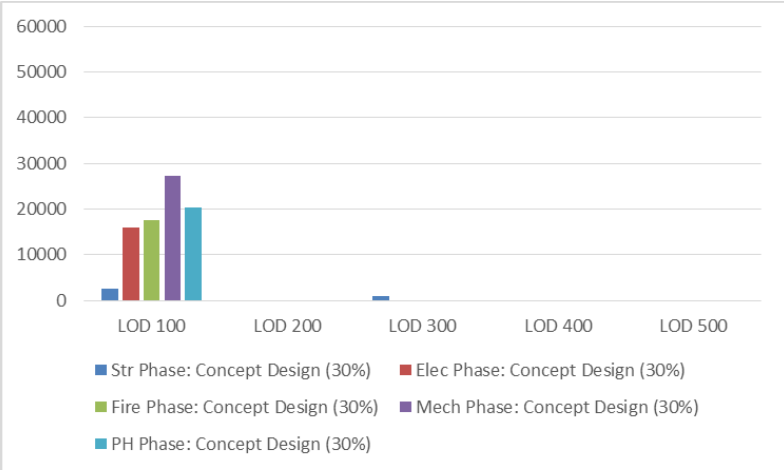


Figure 50 LOD across all disciplines of the model in Concept Design Stage (30%)

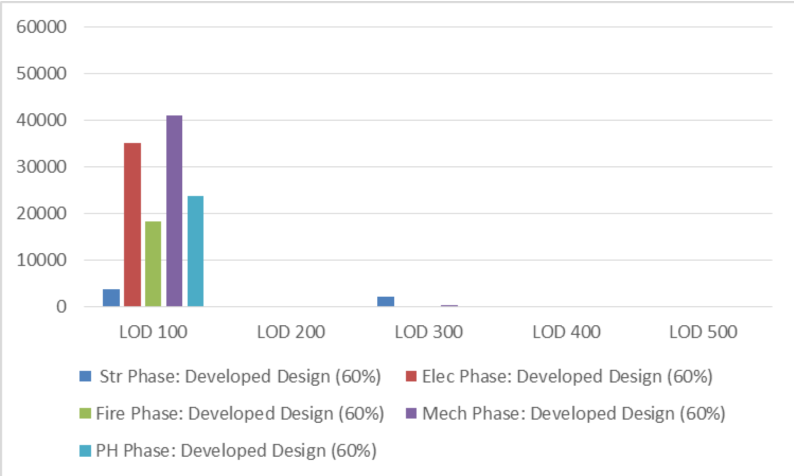


Figure 51 LOD across all disciplines of the model in Developed Design Stage (60%)

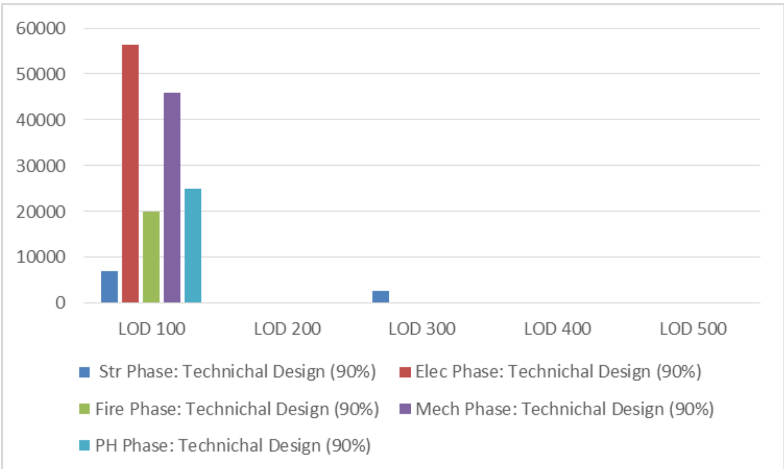


Figure 52 LOD across all disciplines of the model in Technical Design (90%)

8.9 Discussion and conclusion

Although there has been an increasing interest in the field of BIM-AMs in the last decade, very little research has been directed towards the automation of these methods. Throughout the literature of BIM measurement, it has been observed that most existing AMs include a large number of qualitative measures that involve personal judgements by assessors. This makes it difficult to create repeatable, reliable and consistent outcomes. When AMs were applied in practice, Chapters 6 and 7, it was evident that having different assessors of the same project leads to different outcomes. It was also observed that some AMs require hours to complete. In order to overcome these pressing challenges, automation is seen to be one of the key solutions for the future of BIM-AMs.

In this chapter, an automated approach to evaluating BIM has been introduced. The automated BIM-AM is designed to check each model element and the amount of information attached to it. It runs through many thousands of elements and offers an illustration of their LOD. This level of scalability has not been enabled in current BIM-AMs, where LOD is evaluated on the model level as a whole, not its individual elements. The automated approach provides professionals with a rapid and accurate feedback on their project. After analysing this feedback, they can have an overall illustration of the LOD of their models and take action if further information (such as materials, cost and phase) is needed or changes to their working practices are needed.

Comparison of the findings across Phase 1 and Phase 2 is difficult since models include different project disciplines, and because they have been evaluated differently. In Phase 1, the AM was applied to multiple projects once, whereas in Phase 2, the AM was applied three times to one model to investigate the changes of LOD across project stages. However, one common trend was observed in the two phases in mechanical and electrical models, where all elements were allocated LOD 100.

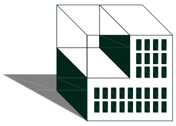
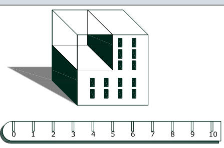
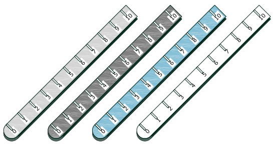
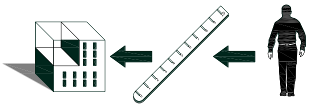
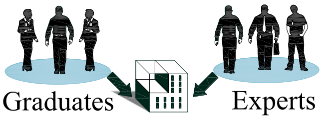
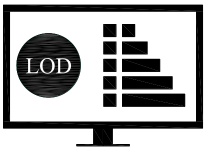
The testing undertaken in Phase 2 shows that more elements are being added to the model throughout the development stages. However, additional elements do not mean higher LOD of the overall model, but perhaps, higher level of definition and information. As observed in the testing, which also matched the standard provided by the company, some elements added to the model at later project stages have only LOD 100, since they might be determined by other stakeholders. This is expressed by the BIM Development Manager interviewed in this research:

> The main difference between 200 and 300 in my mind, the discussion we have had internally, is that LOD 200 is a generic bit of equipment. LOD 300 is a specific bit of equipment. So if you are modelling something like a pump, you can make the space arrangement for a pump of a certain capacity and that would be 200. Once you have chosen the pump, it becomes 300. It is not necessarily our role to choose any specific bit of equipment, which means the vast majority of our model really should only ever reach LOD 200.

More research is needed in the area of automated BIM-AM. In this chapter, an automated AM has been introduced to evaluate the LOD of model elements. Future automated methods should focus on creating more comprehensive assessments that evaluate multiple measures. More implementation of automated AMs in practice will be also recommended. Future research opportunities in BIM-AMs are enormous and will be discussed in Chapter 9.

9 Conclusions and future directions

This research has broadened the understanding of BIM-AMs across many aspects, including the evolution of AMs over the last decade, their opportunities and challenges, and their potential for automation. All these aspects have been discussed over the course of this thesis, which together extend and challenge what is already known about BIM-AMs. In this chapter, conclusions from the body of the thesis are presented, and limitations for further research are set out.

1: Introduction	**2: PMSs**	**3: BIM-AMs**
		
Main questions included: What is BIM? What is the need for BIM-AMs?	Includes: - Brief history of the broad PMSs, their definitions - PMSs roles and barriers - Sample of PMSs	- Explains the wide range of BIM-AMs, their evolution, opportunities and challenges - Investigates how BIM-AMs have been informed by the broader PMSs
4: Research methodology	**5: Perspectives on BIM-AMs**	**6: Pilot Testing**
		
Introducing the chosen research methods including questionnaire, interview and the implementation of multiple AMs in practice	- Critical analysis of the BIM-AM, their similarities and differences - This includes the design process, the complexity and the range of measures	Initial testing of individual and multiple AMs in practice in association with a number of practices
7: Comprehensive testing	**8: Automated BIM-AM**	**9: Conclusions**
		
In association with Arup, applying three AMs to the same project and completed by six participants who have different BIM experience i.e. experts and graduates	Includes: - The need for automated AMs - The implementations of BIM-AM in practice	Current perspectives and future directions of BIM-AMs

9.1 Revision of the research aim and objectives

It was hypothesised in this thesis that inconsistency is one of the main challenges of current AMs, since they rely heavily on subjective and qualitative measures. It was also hypothesised that automation might have the potential to optimise existing AMs and provide quick and accurate feedback on BIM's implementation (explained in Section 3.8). To test these two hypotheses, research identified perspectives which help the AEC businesses to develop and implement BIM-AMs in practice.

The reviewed literature in Chapters 2 and 3 addressed the initial aim of this thesis. They explored the evolution of BIM-AMs over the last decade and the forces that have shaped their development. Chapter 5 provided a more overarching approach that compared existing AMs and investigated their similarities and differences in order to address the first research objective i.e. to better understand the relationship between current AMs. Observations have shown that more recent AMs have been influenced by past assessments. It was also shown that the research field of BIM-AMs in general has been widely shaped by AMs in diverse research disciplines in terms of design process, communication of results and the use of maturity levels.

The second research objective, which deals with the consistency and subjectivity of BIM-AMs, was investigated in Chapters 6 and 7. To address this point, multiple existing AMs were applied in practice to assess their consistency. Findings support the first hypothesis (the inconsistency of current AMs) since it was found that two participants completing the same AM on the same project led to completely different results.

In Chapter 7, an in-depth case study was carried out in association with Arup. Observations showed that there is a link between the level of consistency and the level of experience of participants. Those who have more knowledge and a higher level of engagement in the BIM process make more similar assessments when compared to graduates who have more contrasted outcomes. In addition, the level of consistency across different AMs is varied. Some AMs, such as the BIM-MM, are more likely to result in similar outcomes when completed by different participants.

Chapter 8 covered the third objective of this thesis, which automates an element of BIM assessment. The created plug-in can evaluate elements in a BIM model in regard to the level of detail they contain. It offers an overall reflection of the information embedded in the model in a quick and accurate manner. This opens new opportunities in the research field of BIM-AMs.

9.2 Contribution to knowledge

The research carried out by the author is significant for several reasons. First, it includes one of the very few studies that comprehensively address the question of how BIM-AMs have evolved over the last decade and how they have been shaped by other research disciplines. Various researchers introduce and promote new AMs, but few explore the history of these AMs, their design process, their focus, content and their ways of communicating results. This study is the only which includes the sixteen currently available AMs as a coherent whole. Second, the adopted research method is unique. Instead of examining a single AM through CSPs in practice, multiple AMs were applied in different phases to explore score comparisons (Section 6.2), user comparisons (Section 6.3) and model comparisons (Section 6.4). This was followed by an overarching test carried out in association with Arup (discussed in Chapter 7) to compare the AMs when completed by different participants who have different levels of BIM experience.

Third, the study contributes to the current literature of AMs, by automating the process of BIM measurement (explained in Chapter 8). Instead of focusing on qualitative ways of measuring BIM, the work undertaken for this thesis has created a new automated approach to evaluate one aspect of BIM. This has not been explored in the current literature. This combination of theory and practice builds a valuable foundation based on in-depth research for academics, professionals and policy-makers interested in BIM measurement.

9.3 Key findings and conclusions

This thesis began with recognition that with the growing interest in BIM from academics, governments and professionals, and with the shortage of documentation on how to implement and evaluate BIM, there is an urgent need for BIM-AMs. Since 2007, there has been long-standing recognition that the development of AMs in the BIM domain assists professionals to evaluate their BIM competencies and enables them to gain feedback on BIM utilisation. This feedback is beneficial for AEC professionals to improve BIM maturity levels and identify areas of strengths and weaknesses. Yet, it has been observed that the history of BIM-AMs' evolution has been under-explored. This is in part because most studies on BIM measurement have been concerned with promoting and introducing their own AMs without comprehensively investigating the total picture of the BIM-AM research field. With few exceptions, existing studies have failed to explain how AMs have been developed and how they are likely to evolve in the future.

However, today there are opportunities to take an alternative approach. There is a need to look beyond introducing individual AMs and move towards a broader and more collective research approach. As performance measurement scholars in different research fields have acknowledged, a collective understanding of AMs of a specific research field is of vital importance. This is similar in the BIM domain since collective approaches have the potential to enrich the current research agenda and help to provide a solid foundation for more in-depth research.

This thesis has taken an interdisciplinary approach to explore BIM-AMs. The research has offered a starting point that combines theory and practice for thinking about the development of BIM-AMs. On the theoretical side, the research goes beyond available literature on BIM measurement since it draws attention to the wider research field. It looks holistically at BIM-AMs, their definitions, origins and characteristics, gives examples of remarkable AMs along with potential opportunities and challenges for adoption. It also summarises the ways AMs have been designed and the research methods applied for development, and identifies future research directions. On the practical side, multiple AMs are applied in association with different AEC companies in the UK to better understand the opportunities and challenges of current AMs and to investigate BIM's maturity across these companies. In addition, an automated element of BIM measurement was developed and applied to create fast and accurate feedback on the LOD of models.

Throughout the thesis, several themes can be extracted. The following themes will be of particular interest to those researchers, developers and other professionals working on BIM implementation and measurement in the built environment.

9.3.1 Two main forces influence the development of BIM-AMs

What has been lacking in the current literature of BIM measurement is a focus on the forces and influences that impact the development of BIM-AMs, a gap that has been addressed in this thesis. It has been shown that there are two main forces help shaping the emergence of BIM-AMs. These forces are (1) external forces from different research disciplines, such as software engineering, environmental buildings and business management and (2) internal forces where AMs have built upon previous ones and were influenced by the emerging themes in the BIM domain. Together, these two forces impacted BIM-AMs on different levels including their content, the use of maturity levels, the way the outcomes being communicated and the overall structure of the assessment.

9.3.2 BIM-AMs entail more than evaluation

One of the most obvious aims of AMs is to 'measure' BIM across projects, organisations, teams or individuals. However, it is important to note that BIM-AMs, as with other AMs in different research disciplines, move beyond 'evaluation'. Indeed, AMs have the potential to generate greater levels of communication between different engaged stakeholders. Today, AEC businesses have to explain to clients and employees the full potential of BIM; a challenging task because of the uncertainty surrounding BIM definition and the different levels of BIM knowledge and experience of those stakeholders.

However, by using AMs, managers can translate their BIM visions and strategies into a set of structured measures. AM, can help managers to create a common language across the multiple levels of their businesses as well as with their clients. At the early stage of each project, AMs can be used by managers to introduce their strategies and communicate their desired level of maturity of each evaluated measure. This will in turn enhance a dialogue of BIM between different engaged project teams. In particular, this would be valuable for those involved in the project, but with less experience of BIM, since AMs would enable them to understand the overall picture of BIM and its most critical elements. This has been observed when applying AMs in practice. Participants had to discuss some of the measures with their colleagues to complete the assessments. In addition, the BIM Development Manager (in Section 7.5) explained how, through the use of AMs, outcomes could be communicated, opening a conversation with clients on what is BIM and how to get the best value from it.

9.3.3 Current BIM-AMs paint different pictures of BIM

In observing and implementing different AMs, it has been seen that current AMs do not rely on one set of measures (although they overlap in some instances). Each of these different AMs puts BIM in a different context according to the developers' aim and focus. The NBIMS-CMM applied in Chapters 6 and 7, includes measures related to information management, such as data richness, delivery methods, information accuracy and business process. NBIMS-CMM has therefore been criticised for considering only this aspect of BIM.

Later emerging AMs, such as the VDC Scorecard and the BIM-MM, offer a broader range of measures, and more balanced approach that look at the multi-faceted dimensions of BIM. In the VDC Scorecard for instance, four main areas of BIM are addressed, namely planning, adoption, technology and performance. In the BIM-MM, broad areas of BIM are considered, including BIM Champion, BIM contract and Common Data Environment.

Different BIM-AMs showed significantly variable results when applied to the same project, and the critical question to be asked here is which one should be trusted? In Section 6.4, two AMs were applied to a 'Private Schools Project'. The findings showed that the project was allocated to "Minimum BIM" when applying the NBIMS-CMM and "Advanced Practice" when applying the VDC Scorecard. Similar outcomes were reported when repeating this scenario on a 'University Building Project'. This was also evidenced in the more in-depth testing carried out in Chapter 7. An explanation of this contradiction between the different AMs' outcomes is that current AMs have different definitions of what is the best BIM project and rather than arguing which AM is the best, it is crucial to use these AMs more intelligently. A diversification of AMs can enhance a more inclusive approach of BIM measurement. Professionals, researchers and policy-makers should acknowledge that these AMs shed different lights on BIM and measure different set of areas.

9.3.4 There is a lack of awareness of current BIM-AMs despite the recognition of their need

Previous pioneering research has already taken place on BIM measurement, drawing attention to different possible ways of evaluating BIM. What is missing, however, are studies that apply BIM-AMs in practice and bridge the gap between research and the AEC industry. This in turn has led to a lack of awareness of current BIM-AMs across the BIM community. With the competitive global market across the AEC industry, and the governments' strategies for BIM implementation, there is a need for efficient ways to measure BIM and disseminate its potential. This need has been acknowledged by all BIM professionals participating in this research (questionnaire survey in Section 7.1.2). According to them, AMs are needed to explore opportunities and challenges, compare different companies, track progression and measure return on investment.

However, despite this recognition, BIM-AMs are still lagging other disciplines with limited awareness across the AEC community. As discussed in Section 7.1.1, 70% of the participants of the survey were unaware of BIM-AMs. This limited awareness has also been reported in the existing literature by CIFE, the developers of the VDC Scorecard. Going beyond research and collaborating with industry to raise awareness of BIM-AMs was one of the main aims of this thesis. This has led to collaboration with multiple AEC practices in particular with Arup where the outcomes of 213 projects assessed by the BIM-MM were analysed and published at the ARCOM conference, see Appendix B.

9.3.5 Automation offers a new perspective for BIM-AMs

There are critical challenges of current AMs related to repeatability, reliability and accuracy. The credibility of AMs within the AEC businesses is mainly based on the consistency of the assessment. This research has shown that two participants working in the same company and on the same project can produce significantly contrasting evaluation outcomes when applying the same AM. This has not been observed in only one of the AMs, but with all the applied AMs in Chapters 6 and 7. A possible explanation of this inconsistency might be because current AMs rely heavily on qualitative measures which involve personal judgement of the assessor, or because of the lack of clarity and the inadequate guidance included in some of the current AMs. What has been largely missing in the current literature of BIM-AMs, is an approach that offers a sharper, more efficient and a consistent way to carry out the process of BIM measurement.

An automated approach provides a fast and a user-friendly assessment for the AEC businesses. The automated plug-in developed in this thesis turns qualitative and subjective measures into quantifiable and objective data, enables testing of thousands of elements of the digital model and highlights the LOD of each element, as discussed in Chapter 9. Based on the outputs, managers prioritise and draw steps that should be taken to increase the LOD of the project elements if needed. The scope of the developed plug-in is broad and expands to include not just all stages but broaden out away from just LOD. Professionals and mangers can have a quick and accurate evaluation as project progresses.

9.3.6 Summary

Since 2007, the research field of BIM-AMs has matured with at least sixteen AMs developed by academics and professionals. Considerable research continues to be made in an attempt to introduce and promote new AMs that overcome the shortcomings of previous ones. In this thesis, the research did not set out to focus on the introduction of a new AM, but rather, it explores the relationship between the existing AMs and provides a comprehensive view of BIM measurement. It also applies a sample of AMs in the AEC industry, which is essential to evaluate BIM levels of maturity, sheds light on how BIM is being used in practice, and observes the strengths and weaknesses of the applied AMs.

9.4 Recommendations

In line with the objectives and the conclusions of this research, a number of recommendations are suggested for researchers, professionals and policy-makers working on BIM-AMs:

- It is not enough to implement BIM-AMs in practice, but more significantly, outcomes should be systematically analysed and communicated in various ways to gain more insights on BIM maturity levels.
- Researchers and professionals interested in BIM measurement should explore previous AMs in the BIM literature and across different research fields to learn lessons and avoid past limitations.
- AEC professionals should apply the BIM-AMs more intelligently and explore their various roles not only as methods of BIM evaluation but also as a way of communicating strategies and goals.
- The relationship between BIM-AMs' researchers and professionals should be reinforced.

9.5 Limitations and future research

Throughout the thesis, a significant body of theoretical and practical research on BIM-AMs has been documented. This combination of theory and practice has generated a better understanding of BIM-AMs, their opportunities and importance and also their limitations and challenges. With the emergence of BIM-AMs, research across a range of areas will evolve; diverse measures will be added, further implementation of AMs in practice will be undertaken, more efforts will be directed towards transforming the outcomes into meaningful source of information, new optimised AMs will be created and more collaboration with researchers and professionals will be needed.

9.5.1 New measures should be addressed and AMs should be updated

Assessing information management, as suggested in NBIMS-CMM, is an essential part of BIM performance measurement. However, these types of measure by themselves (i.e. data exchange and data richness and graphical information) are not enough to reflect the full picture of BIM. The multi-faceted aspects of BIM, and the evolving environments of the AEC business, has led to the emergence of new measures that mirror the evolving technologies, processes and policies surrounding BIM.

To respond to these changing environments, managers and researchers have to ensure that the measures they include in their AMs are kept relevant as businesses evolve. In the broader literature of performance measurement systems it has been shown that early developments of business measurement focused only on financial measures. Such developments were heavily criticised for reflecting only part of the business rather than addressing its diverse elements. This led to a wave of new models that included not only the financial measures but also the non-financial ones.

Similarly, in the BIM domain, it is crucial to revisit and re-engineer AMs once they have been developed; a critical issue that has not been addressed in current BIM-AM literature. For instance, NBIMS-CMM, the first developed BIM-AM, was released in 2007, updated in 2013 and later in 2015. Whilst it is good to see it is updated, the measures included in this model were kept exactly the same without removing or adding any. The updated versions expanding their reviewed literature and changed the required scores to achieve 'Minimum BIM' maturity level. In contrast, the developers of BIM-MM have recently acknowledged the need to re-engineer their model and plan to add new measures will be added to the model, particularly, financial measures.

New perspectives and insights of AMs should address the future direction of BIM. For instance, there is little information about the use of BIM by facility managers for maintenance and operation. AM research should cover measures that evaluate the use of BIM in the post-construction stage. This would be crucial to offer more confidence to clients that BIM models should be used throughout the life-cycle of a project, which is believed to be a fundamental benefit of BIM. Developers of BIM-AMs should focus on re-designing their models as time passes. Adding new measures and deleting obsolete ones is of vital importance to capture the changing nature of the AEC industry, its technologies and capabilities. Re-visiting the choice of measures needs to be built-in to the AM process.

9.5.2 Further Case Study Projects should be carried out in the field of BIM-AMs

A large number of new Case Study Projects (CSPs) are needed to provide an in-depth investigation of BIM-AMs. It was observed in Section 5.7 that there is a lack of research directed towards the implementation of BIM-AMs in practice. Although at least sixteen BIM-AMs have been developed over the last decade, only half of them have been supplemented with publications on CSPs. Implementation in practice is essential for AM's developers to validate their AM and to understand its strengths and weaknesses. This will help to shift the research field from its theoretical background into a practical context.

9.5.3 Collaboration network between BIM measurement researchers should be created

This was partially applied in this thesis, where BIM-AMs' developers were contacted to exchange ideas and find out more about their AMs. This included the developers of the NBIMS-CMM, the BIM Excellence and BIM Maturity Matrix, the VDC Scorecard, bimSCORE and the BIM-MM. Future research should focus on carrying out formal interviews with developers of all existing AMs to explore experts' views, opinions and attitudes towards BIM measurement, which has not yet been discussed elsewhere in the existing literature. Researchers might use these interviews to create frameworks that help answer some of the key questions surrounding AMs, including the way appropriate measures should be selected and the possible approaches to design. Furthermore, a professional network should be created to strengthen the relationship between the researchers and professionals of the BIM measurement community. This has not yet been initiated and might help to open new opportunities for BIM-AMs research.

9.5.4 Data should be transformed into meaningful information

Producing data by applying AMs to multiple projects in itself is not enough. Research must be carried out to transform the collected data into clear and meaningful feedback that can drive change in businesses. Breaking down the findings into different categories will enable users to interpret the data and draw valuable conclusions. This will help to compare findings across countries, teams, and projects, which inform future decision making process. Examples of data analysis are:

- By project stage: to demonstrate the development of BIM utilisation throughout project's life cycle.
- By geography: once collected, data can be classified geographically to exhibit the variation of BIM maturity levels across cities and countries. Exhibiting this classification via maps might reveal how BIM is being used nationally and internationally.
- By project team: multiple teams will be involved with the same project including architects, civil, mechanical and electrical engineers. Evaluating BIM maturity according to which project team is carrying out the work offers an illustration of which team has the highest maturity levels of a range of projects. Teams with higher levels

across projects maturity can accordingly assist and help support teams with lower levels of maturity.

- By individual project: companies can compare projects against each other and distinguish high and low scores across projects. Companies can therefore focus on the projects that have high maturity levels and understand how projects with low levels can be improved.
- By measure: companies can identify the relationship between measures and the impact of one particular measure on the overall score of the project. This has been investigated by the author when observing the relationship between the engagement of the BIM Champion and the overall scores of projects, as in Appendix B.

To make the most of these outcomes, findings should be clearly communicated in a user-friendly format that sends clear messages to AEC professionals, researchers, policy-makers and clients. Findings should be communicated in various ways i.e. numerically, narratively, visually, and interactively. Different mediums will be more appropriate for different audiences. For instance, visual informative geographical maps can be used to compare BIM levels of maturity across cities and countries with different colours to present maturity to policy-makers.

9.5.5 BIM-AMs' design should be further explored

The design process of AMs has been the subject of considerable study across different research disciplines, however it has been rarely discussed in the BIM domain. Although current AMs have contributed significantly to the field of BIM measurement, many have offered little documentation on how the selected measures were identified. This gap in literature should be further explored to assist managers and researchers designing their own AMs. It is recommended that future studies should review the design process of AMs in the wider literature of performance measurement with particular focus on BIM. These studies should focus on possible development approaches of AMs, rather than designing and introducing new AMs. The information collected in such studies should be analysed and organised in the form of a set of guidelines that enriches the understanding of the design process of AMs. Accordingly, developers of AMs can explore the successful research methods (such as focus groups, surveys and interviews) that can be adopted when deciding what to measure and how to populate these AMs.

Other recommendations include training assessors (so results can be more consistent) and strengthening the relationship between the academic industry communities to combine theory with practice in order to achieve more efficient and effective methods of evaluating BIM.

9.5.6 New optimised BIM-AMs will emerge

Following the development of the sixteen AMs over the last decade, it is expected that new AMs will continue to emerge in the BIM domain by academics and professionals. Such AMs will offer new insights and perspectives of BIM measurement with different sets of measures, and priorities. However, researchers and AEC professionals interested in developing new frameworks have to observe the history of this field to seek guidance, to learn lessons and avoid past fundamental obstacles that include subjectivity, lack of implementation in practice and a shortage of instructions on how to use the developed AM.

Emerging AMs should introduce new ways of quantifying BIM benefits, by including not only subjective measures but also objective ones. By doing so, future AMs will enable more accurate and reliable evaluation systems.

Emerging AMs might also apply automation whenever possible to evaluate BIM levels of maturity. Automated AMs offer quick, accurate and user-friendly methods of evaluation rather than relying on human judgement and taking hours to complete as is the case with some of the existing AMs. The pioneering advances of automation have the potential to make BIM measurement an integral part of the AEC industry since they are easy to apply and fast to create feedback. In this thesis, an automated AM was developed to evaluate the Level of Detail (LOD) of BIM elements. Future research might consider other opportunities to include more integrated measures including time spent building the model, data exchange methods, clash detection, and number of participants creating the model. Assessing multiple measures in an automated fashion will offer ample perspectives for future studies.

References

Ahmad, A. M. (2014). *The use of refurbishment, flexibility, standardisation and BIM to support the design of a change-ready healthcare facility.* © Ahmad Mohammad Ahmad.

Ahmad, M., Demian, P., & Price, A. D. (2012). BIM implementation plans: A comparative analysis. *Management, 33*, 42.

AIA, A. (2008). Document E202-2008. *Building Information Modeling Protocol Exhibit, Washington, DC: American Institute of Architects*.

Arayici, Y., Coates, P., Koskela, L., Kagioglou, M., Usher, C., & O'reilly, K. (2011). Technology adoption in the BIM implementation for lean architectural practice. *Automation in Construction, 20*(2), 189-195.

Arup. (2014). The BIM Matuity Measure model. 26.02.2016, from http://www.arup.com/Services/Building_Modelling.aspx

Atkinson, A. A., Waterhouse, J. H., & Wells, R. B. (1997). A stakeholder approach to strategic performance measurement. *MIT Sloan Management Review, 38*(3), 25.

AUTODESK. (2014). Bulding Information Modeling Retrieved 30.06.2014, from http://www.autodesk.com/solutions/building-information-modeling/overview

Azhar, S. (2011). Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry. *Leadership and Management in Engineering, 11*(3), 241-252.

Azhar, S., Hein, M., & Sketo, B. (2008). *Building information modeling (BIM): Benefits, risks and challenges.* Paper presented at the Proceedings of the 44th ASC National Conference.

Azhar, S., Khalfan, M., & Maqsood, T. (2012). Building information modeling (BIM): now and beyond. *Australasian Journal of Construction Economics and Building, The, 12*(4), 15.

Azzouz, A., Copping, A., Shepherd, P., & Duncan, A. (2016). *Using the Arup BIM Maturity Measure to Demonstrate BIM Implementation in Practice* Paper presented at the ARCOM, Manchester.

Azzouz, A., Shepherd, P., & Copping, A. (2016). *The emergence of Buildign Information Modelling Assessment Methods (BIM-AMs)*. Paper presented at the Integrated Design Conference, University of Bath, UK.

Bagnoli, A. (2009). Beyond the standard interview: The use of graphic elicitation and arts-based methods. *Qualitative research, 9*(5), 547-570.

Baker, M. J. (2003). *Business and management research : how to complete your research project successfully*. Helensburgh: Helensburgh : Westburn.

Baraldi, S., & Cifalinò, A. (2015). Delivering training strategies: the balanced scorecard at work. *International Journal of Training and Development, 19*(3), 179-198. doi: 10.1111/ijtd.12055

Barlish, K., & Sullivan, K. (2012). How to measure the benefits of BIM — A case study approach. *Automation in Construction, 24*(0), 149-159. doi: http://dx.doi.org/10.1016/j.autcon.2012.02.008

Baxter, P., & Jack, S. (2008). Qualitative case study methodology: Study design and implementation for novice researchers. *The qualitative report, 13*(4), 544-559.

Beach, T. H., Kasim, T., Li, H., Nisbet, N., & Rezgui, Y. (2013). Towards Automated Compliance Checking in the Construction Industry. In H. Decker, L. Lhotská, S. Link, J. Basl, & A. M. Tjoa (Eds.), *Database and Expert Systems Applications: 24th International Conference, DEXA 2013, Prague, Czech Republic, August 26-29, 2013. Proceedings, Part I* (pp. 366-380). Berlin, Heidelberg: Springer Berlin Heidelberg.

Becker, J., Knackstedt, R., & Pöppelbuß, D.-W. I. J. (2009). Developing maturity models for IT management. *Business & Information Systems Engineering, 1*(3), 213-222.

Bedrick, J. (2008). Organizing the development of a building information model. *The American Institute of Architects, 9*.

Behn, R. D. (2003). Why measure performance? Different purposes require different measures. *Public administration review, 63*(5), 586-606.

Bennett, A. (2004). Case study methods: Design, use, and comparative advantages. *Models, numbers, and cases: Methods for studying international relations*, 19-55.

Bergman, M. M. (2008). *Advances in Mixed Methods Research Theories and Applications*. London

Berlo, L., Dijkmans, T., Hendriks, H., Spekkink, D., & Pel, W. (2012). BIM quickscan: benchmark of BIM performance in the Netherlands. *CIB W78*.

BIM Forum. (2015). Level of Development Specification for Building Information Models.

BIM Industry Working Group. (2011). A Report for the Government Construction Client Group Building Information Modelling (BIM) Working Party Strategy Paper: Cabinet

Office. Retrieved from http://www. bimtaskgroup. org/wp-content/uploads/2012/03/BIS-BIM-strategy-Report. pdf.

BIM Task Group. (2013). What is Building Information Modelling (BIM)? *Frequently Asked Questions.* Retrieved 30.06.2014, from http://www.bimtaskgroup.org/bim-faqs/

bimSCORE. (2013). bimSCORE. Retrieved 26.02.2016, from https://www.bimscore.com/index.php/welcome

Bititci, U., Garengo, P., Dörfler, V., & Nudurupati, S. (2012). Performance measurement: Challenges for tomorrow*. *International Journal of Management Reviews, 14*(3), 305-327.

Boote, D. N., & Beile, P. (2005). Scholars before researchers: On the centrality of the dissertation literature review in research preparation. *Educational researcher, 34*(6), 3-15.

Bourne, M., Melnyk, S., Faull, N., Franco-Santos, M., Kennerley, M., Micheli, P., . . . Gray, D. (2007). Towards a definition of a business performance measurement system. *International journal of operations & production management, 27*(8), 784-801.

Bourne, M., Mills, J., Wilcox, M., Neely, A., & Platts, K. (2000). Designing, implementing and updating performance measurement systems. *International journal of operations & production management, 20*(7), 754-771.

Bourne, M., Neely, A., Mills, J., & Platts, K. (2003). Implementing performance measurement systems: a literature review. *International Journal of Business Performance Management, 5*(1), 1-24.

Brannen, J. (1992). *Mixing methodsqualitative and quantitative research*.

BRE. (2015a). BIM Level 2 Business Systems Certification. Retrieved 26.02.2016, from http://www.bre.co.uk/page.jsp?id=3389

BRE. (2015b). BIM Level 2 Certificated Practitioner Scheme. Retrieved 26.02.2016, , from http://www.bre.co.uk/BIMBSCListings

BREEAM. (2015). What is BREEAM. Retrieved 27/01/2015, from http://www.breeam.org/about.jsp?id=66

Brinkmann, S. (2014). *Interview*: Springer.

Britten, N. (1995). Qualitative research: qualitative interviews in medical research. *Bmj, 311*(6999), 251-253.

Bryde, D., Broquetas, M., & Volm, J. M. (2013). The project benefits of Building Information Modelling (BIM). *International Journal of Project Management, 31*(7), 971-980. doi: http://dx.doi.org/10.1016/j.ijproman.2012.12.001

Bryman, A. (2004). *Social research methods* (2nd ed. ed.). Oxford: Oxford : Oxford University Press.

Bryman, A. (2012). *Social research methods* (4th ed. ed.). Oxford: Oxford : Oxford University Press.

Cao, D., Wang, G., Li, H., Skitmore, M., Huang, T., & Zhang, W. (2015). Practices and effectiveness of building information modelling in construction projects in China. *Automation in Construction, 49*, 113-122.

Caramani, D. (2009). *Introduction to the comparative method with Boolean algebra*. Los Angeles: Los Angeles : SAGE.

Change Agents AEC. (2013). BIM Excellence Performance Measurement Coporate Services

Chen, K. (2015). *A Strategic Decision Making framework for Organisational BIM implementation.* Cardiff University.

Chen, Y., Dib, H., & Cox, R. F. (2012). *A Framework for Measuring Building Information Modeling Maturity in Construction Projects.* Paper presented at the 14th International Conference on Computing in Civil and Building Eingeering, Moscow, Russia.

CIBSE. (2015). New tool to measure projects' BIM use. *Chartered Institution of Building Services and Engineers*.

CIC. (2013). BIM Planning Guide for Facility Owners. Version 2.0. Retrieved from: http://bim.psu.edu/

CIFE. (2013). CIFE VDC Scorecard Research Website from http://cife.pbworks.com/w/browse/#view=ViewFolder&param=Dimi

Cole, R. J. (1998). Emerging trends in building environmental assessment methods. *Building Research & Information, 26*(1), 3-16.

Cole, R. J. (2005). Building environmental assessment methods: redefining intentions and roles. *Building Research & Information, 33*(5), 455-467.

Cole, R. J. (2006). Shared markets: coexisting building environmental assessment methods. *Building Research & Information*, *34*(4), 357-371.

Cole, R. J., & Jose Valdebenito, M. (2013). The importation of building environmental certification systems: international usages of BREEAM and LEED. *Building Research & Information, 41*(6), 662-676.

Collier, D. (1993). The comparative method. *Political Science: The State of Discipline II, Ada W. Finifter, ed., American Political Science Association*.

CPI. (2011). CPIx-BIM Assessment Form. http://www.cpic.org.uk/wp-content/uploads/2013/06/cpix_-_bim_assessment_form_ver_1.0.pdf

Crawford, J. K. (2007). *Project management maturity model*: Taylor & Francis.

Crawford, J. K. (2014). *Project management maturity model*: CRC Press.

Crawley, D., & Aho, I. (1999). Building environmental assessment methods: applications and development trends. *Building Research & Information, 27*(4-5), 300-308.

Creswell, J. W. (2009). *Research design : qualitative, quantitative, and mixed methods approaches* (3rd ed. ed.). Los Angeles, Calif.

Creswell, J. W. (2013). *Research design: Qualitative, quantitative, and mixed methods approaches*: Sage publications.

Crosby, P. B. (1979). *Quality is Free: The Art of Making Quality Certain*: McGraw-Hill.

Dakhil, A. (2015). BIM Client Maturity: Literature Review.

Dakhil, A., & Alshawi, M. (2014). Building Information Modelling Benefits-Maturity Relationship from Client Perspective.

Dawson, C. (2002). Practical Research Methods. A user-friendly guide to mastering research techniques and projects. Magdalen Road: Oxford OX4 1RE. United Kingdom.

De Bruin, T., Freeze, R., Kaulkarni, U., & Rosemann, M. (2005). Understanding the main phases of developing a maturity assessment model.

de Haas, M., & Kleingeld, A. (1999). Multilevel design of performance measurement systems: enhancing strategic dialogue throughout the organization. *Management Accounting Research, 10*(3), 233-261. doi: http://dx.doi.org/10.1006/mare.1998.0098

Demian, P., & Walters, D. (2014). The advantages of information management through building information modelling. *Construction Management and Economics, 32*(12), 1153-1165.

Denscombe, M. (2014). *The good research guide: for small-scale social research projects*: McGraw-Hill Education (UK).

Dib, H., Chen, Y., & Cox, R. (2012). *A framework for measuring building information modeling maturity based on perception of practitioners and academics outside the USA.* Paper presented at the Proceedings 29th.

Ding, G. K. C. (2008). Sustainable construction—The role of environmental assessment tools. *Journal of Environmental Management, 86*(3), 451-464. doi: http://dx.doi.org/10.1016/j.jenvman.2006.12.025

Dossick, C. S., & Neff, G. (2010). Organizational Divisions in BIM-Enabled Commercial Construction. *Journal of construction engineering and management, 136*(4), 459-467. doi: doi:10.1061/(ASCE)CO.1943-7862.0000109

Eastman, C., Jeong, Y.-S., Sacks, R., & Kaner, I. (2009). Exchange model and exchange object concepts for implementation of national BIM standards. *Journal of Computing in Civil Engineering, 24*(1), 25-34.

Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2011). *BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors*: Wiley. com.

Elsevier. (2015). Scopus. Retrieved 02/03/2015, from http://www.elsevier.com/online-tools/scopus

EU BIM Task Group. (2016). EU BIM Task Group. Retrieved 09/11/2016, from http://www.eubim.eu/

Fellows, R. F., & Liu, A. M. (2009). *Research methods for construction*: John Wiley & Sons.

Fowler Jr, F. J. (2013). *Survey research methods*: Sage publications.

Franklin, K. K., & Hart, J. K. (2007). Idea Generation and Exploration: Benefits and Limitations of the Policy Delphi Research Method. *Innovative Higher Education, 31*(4), 237-246. doi: 10.1007/s10755-006-9022-8

Gao, J. (2011). *A Characterization Framework to Document and Compare BIM Implementations on Construction Projects.* Stanford University.

Gerring, J. (2004). What is a case study and what is it good for? *American political science review, 98*(02), 341-354.

Gerring, J. (2006). *Case study research: Principles and practices*: Cambridge University Press.

Ghalayini, A. M., Noble, J. S., & Crowe, T. J. (1997). An integrated dynamic performance measurement system for improving manufacturing competitiveness. *International journal of production economics, 48*(3), 207-225.

Gibbons, R., & Kaplan, R. S. (2015). Formal Measures in Informal Management: Can a Balanced Scorecard Change a Culture?

Giel, B., & Issa, R. (2014). *Framework for Evaluating the BIM Competencies of Building Owners.* Paper presented at the Computing in Civil and Building Engineering (2014).

Giel, B., & Issa, R. (2015). Framework for Evaluating the BIM Competencies of Facility Owners. *Journal of Management in Engineering*, 04015024. doi: 10.1061/(ASCE)ME.1943-5479.0000378

Giel, B., & Issa, R. R. (2013). *Synthesis of Existing BIM Maturity Toolsets to Evaluate Building Owners.* Paper presented at the Computing in Civil Engineering (2013).

Giel, B., Issa, R. R. A., & Olbina, S. (2010). Return on investment Analysis of Building Information Modelling in Construction. from Nottingham University Press http://www.engineering.nottingham.ac.uk/icccbe/proceedings/pdf/pf77.pdf

Giel, B. K. (2013). *Framework for Evaluating the BIM Competencies of Building Owners*. [Gainesville, Fla: University of Florida.

Gilkinson, N., Raju, P., Kiviniemi, A., & Chapman, C. (2014). Building information modelling: the tide is turning.

Gill, P., Stewart, K., Treasure, E., & Chadwick, B. (2008). Methods of data collection in qualitative research: interviews and focus groups. *British dental journal, 204*(6), 291-295.

Globerson, S. (1985). Issues in developing a performance criteria system for an organization. *International Journal of Production Research, 23*(4), 639-646. doi: 10.1080/00207548508904734

Gómez-Romero, J., Bobillo, F., Ros, M., Molina-Solana, M., Ruiz, M., & Martín-Bautista, M. (2015). A fuzzy extension of the semantic Building Information Model. *Automation in Construction*.

Goodman, C. M. (1987). The Delphi technique: a critique. *Journal of advanced nursing, 12*(6), 729-734. doi: 10.1111/j.1365-2648.1987.tb01376.x

Grady, M. P. (1998). *Qualitative and action research: A practitioner handbook*: Phi Delta Kappa International.

Haapio, A., & Viitaniemi, P. (2008). A critical review of building environmental assessment tools. *Environmental impact assessment review, 28*(7), 469-482.

Hackett, M. (2016). *The Aqua Group guide to procurement, tendering and contract administration*: John Wiley & Sons.

Haron, A. T. (2013). *Organisational readiness to implement building information modelling: A framework for design consultants in Malysia.* University of Salford.

Harvard UCMC. (2013). Getting started with Building Information Modelling: Harvard University.

Harvard University Construction Management Council. (n.d.). Introduction to Building Information Modeling Harvard University.

Hatry, H. P. (2006). *Performance measurement: Getting results*: The Urban Insitute.

HM Government. (2015). Digital Built Britain: Level 3 Building Information Modelling - Strategic Plan.

Hoque, Z. (2014). 20 years of studies on the balanced scorecard: Trends, accomplishments, gaps and opportunities for future research. *The British Accounting Review, 46*(1), 33-59. doi: http://dx.doi.org/10.1016/j.bar.2013.10.003

Hunt, I., Taylor, R. K., Winter, A., Mackie, J. J., & Fisher, D. (2016). Using the balanced scorecard to enhance undergraduate education in a first year business course: A pilot study. *Journal of Education for Business, 91*(3), 132-137. doi: 10.1080/08832323.2016.1140114

Indiana University Architect's Office. (2009a). Building Information Modeling (BIM) Guidelines and Standards for Architects, Engineers, and Contractors.

Indiana University Architect's Office. (2009b). IU BIM Standards. 2015, from http://www.iu.edu/~vpcpf/consultant-contractor/standards/bim-standards.shtml

Institute of Chartered Accountants of Scotland. (1993). *Measurement: The Total Picture - A Discussion Document*: Institute of Chartered Accountants of Scotland.

Isaksson, A., Linderoth, H., Bosch, P., & Lennartsson, M. (2016). *BIM use in the production process among medium sized contractors: A survey of Swedish medium sized contractors.* Paper presented at the 16th International Conference on Computing in Civil and Building Engineering, ICCCBE2016, Osaka, July 6-8, 2016.

Ittner, C. D., & Larcker, D. F. (1998). Innovations in Performance Measurement: Trends and Research.

Jick, T. D. (1979). Mixing Qualitative and Quantitative Methods: Triangulation in Action. *Administrative Science Quarterly, 24*(4), 602-611. doi: 10.2307/2392366

Johnson, R. B., & Onwuegbuzie, A. J. (2004). Mixed methods research: A research paradigm whose time has come. *Educational researcher, 33*(7), 14-26.

Jupp, J. (2013). *BIM Investment: Understanding value, return and models of assessment.* Paper presented at the The 38th Australasian Universities of Building Education Association Conference.

Kajornboon, A. B. (2005). Using interviews as research instruments. *E-journal for Research Teachers, 2*(1).

Kam, C. (2013). Using Objectified Measures to Realize the Promise of BIM *Journal of the National Institute of Building Sciences (US) publication*.

Kam, C. (2015). Managing BIM Projects, Organizations, and Policies: Turning Aspirations into Quantitative Measures of Success. *Building Information Modeling: BIM in Current and Future Practice*, 267-280.

Kam, C., Senaratna, D., Xiao, Y., & McKinney, B. (2013a). The VDC Scorecard: Evaluation of AEC Projects and Industry Trends.

Kam, C., Senaratna, D., Xiao, Y., & McKinney, B. (2013b). The VDC Scorecard: Formulation, Application and Validation. *Stanford University*.

Kaplan, R., & Norton, D. (2004). *Focusing your organization on strategy-with the balanced scorecard*: Harvard Business School Publishing Cambridge.

Kaplan, R., & Norton, D. (2005). The balanced scorecard: Measures that drive performance. *Harv. Bus. Rev., 83*(7-8), 172-+.

Kaplan, R. S., & Norton, D. P. (1995). Putting the balanced scorecard to work. *Performance measurement, management, and appraisal sourcebook, 66*, 17511.

Kaplan, R. S., & Norton, D. P. (1996a). *The balanced scorecard: translating strategy into action*: Harvard Business Press.

Kaplan, R. S., & Norton, D. P. (1996b). Using the balanced scorecard as a strategic management system: Harvard business review Boston, MA.

Kaplan, R. S., & Norton, D. P. (2001). Transforming the balanced scorecard from performance measurement to strategic management: Part I. *Accounting horizons, 15*(1), 87-104.

Kashyap, A. K., & Wilcox, D. W. (1993). Production and Inventory Control at the General Motors Corporation During the 1920's and 1930's. *The American Economic Review*, 383-401.

Kassem, M., Succar, B., & Dawood, N. (2013). A proposed approach to comparing the BIM maturity of countries.

Keegan, D. P., Eiler, R., & Jones, C. (1989). Are your performance measures obsolete? *Management accounting*, 45.

Kemper, E. A., Stringfield, S., & Teddlie, C. (2003). Mixed methods sampling strategies in social science research. *Handbook of mixed methods in social and behavioral research*, 273-296.

Kilmann, R. H., & Mitroff, I. I. (1976). Qualitative versus quantitative analysis for management science: different forms for different psychological types. *Interfaces, 6*(2), 17-27.

King, N., Cassel, C., & Symon, G. (1998). Qualitative methods in organizational research: A practical guide. *Template Analysis*.

Knight, A., & Ruddock, L. (2008). *Advanced research methods in the built environment*. Oxford: Oxford : Wiley-Blackwell.

Kvale, S. (1996). InterViews. An introduction to qualitative research writing: Thousand Oaks, CA: Sage Publications.

Lebas, M. J. (1995). Performance measurement and performance management. *International journal of production economics, 41*(1–3), 23-35. doi: http://dx.doi.org/10.1016/0925-5273(95)00081-X

Lee, G., & Won, J. (2014). *Goal-driven method for sustainable evaluation of BIM project*. Paper presented at the European Conference on Product and Process Modelling (ECPPM), VIenna, Austria

Leite, F., Akcamete, A., Akinci, B., Atasoy, G., & Kiziltas, S. (2011). Analysis of modeling effort and impact of different levels of detail in building information models. *Automation in Construction, 20*(5), 601-609.

Lijphart, A. (1971). Comparative politics and the comparative method. *American political science review, 65*(03), 682-693.

LIN, E. S., ROITHMAYR, R., & Simon, K. (2015). *A Review of BIM Maturity for Tensile Membrane Architecture.* Paper presented at the IASS 2015: Future Vision. Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2015.

Lockamy III, A., & McCormack, K. (2004). The development of a supply chain management process maturity model using the concepts of business process orientation. *Supply Chain Management: An International Journal, 9*(4), 272-278.

Lohman, C., Fortuin, L., & Wouters, M. (2004). Designing a performance measurement system: A case study. *European Journal of Operational Research, 156*(2), 267-286. doi: http://dx.doi.org/10.1016/S0377-2217(02)00918-9

Lynch, R. L., & Cross, K. F. (1991). *Measure Up!: The Essential Guide to Measuring Business Performance*: Mandarin.

Maltz, A. C., Shenhar, A. J., & Reilly, R. R. (2003). Beyond the balanced scorecard:: Refining the search for organizational success measures. *Long Range Planning, 36*(2), 187-204.

Månsson, D., & Lindahl, G. (2016). 3 BIM performance and capability. *Delivering Value with BIM: A Whole-of-life Approach,* 46.

Marr, B., & Neely, A. (2003). Automating the Balanced Scorecard-selection criteria to identify appropriate software applications. *Measuring business excellence, 7*(3), 29-36.

Marsden, P. V., & Wright, J. D. (2010). *Handbook of survey research*: Emerald Group Publishing.

Marshall, M. N. (1996). Sampling for qualitative research. *Family practice, 13*(6), 522-526.

McCormack, K., Willems, J., Van den Bergh, J., Deschoolmeester, D., Willaert, P., Indihar Štemberger, M., . . . Paulo Valadares de Oliveira, M. (2009). A global investigation of key turning points in business process maturity. *Business Process Management Journal, 15*(5), 792-815.

McCuen, T. L., Suermann, P. C., & Krogulecki, M. J. (2012). Evaluating Award-Winning BIM Projects Using the National Building Information Model Standard Capability Maturity Model. *Journal of Management in Engineering, 28*(2), 224-230. doi: 10.1061/(ASCE)ME.1943-5479.0000062

Medori, D., & Steeple, D. (2000). A framework for auditing and enhancing performance measurement systems. *International journal of operations & production management, 20*(5), 520-533. doi: doi:10.1108/01443570010318896

Meng, X., Sun, M., & Jones, M. (2011). Maturity model for supply chain relationships in construction. *Journal of Management in Engineering, 27*(2), 97-105.

Migilinskas, D., Popov, V., Juocevicius, V., & Ustinovichius, L. (2013). The Benefits, Obstacles and Problems of Practical Bim Implementation. *Procedia Engineering, 57*(0), 767-774. doi: http://dx.doi.org/10.1016/j.proeng.2013.04.097

Morlhon, R., Pellerin, R., & Bourgault, M. (2015). Defining Building Information Modeling implementation activities based on capability maturity evaluation: a theoretical model. *SciKA-Association for Promotion and Dissemination of Scientific Knowledge*.

Moullin, M. (2007). Performance measurement definitions: Linking performance measurement and organisational excellence. *International Journal of Health Care Quality Assurance, 20*(3), 181-183.

Naoum, S. G. (2012). *Dissertation research and writing for construction students*: Routledge.

Navon, R. (2007). Research in automated measurement of project performance indicators. *Automation in Construction, 16*(2), 176-188. doi: http://dx.doi.org/10.1016/j.autcon.2006.03.003

Neely, A. (1999). The performance measurement revolution: why now and what next? *International journal of operations & production management, 19*(2), 205-228.

Neely, A. (2005). The evolution of performance measurement research: developments in the last decade and a research agenda for the next. *International journal of operations & production management, 25*(12), 1264-1277.

Neely, A., & Adams, C. (2000). Perspectives on performance: the performance prism. *Handbook on performance measurement", Gee Publishing, London*.

Neely, A., Adams, C., & Crowe, P. (2001). The performance prism in practice. *Measuring business excellence, 5*(2), 6-13.

Neely, A., & Bourne, M. (2000). Why measurement initiatives fail. *Measuring business excellence, 4*(4), 3-7.

Neely, A., Gregory, M., & Platts, K. (1995). Performance measurement system design: a literature review and research agenda. *International journal of operations & production management, 15*(4), 80-116.

Neely, A., Gregory, M., & Platts, K. (2005). Performance measurement system design: a literature review and research agenda. *International journal of operations & production management, 25*(12), 1228-1263.

Neely, A., Marr, B., Roos, G., Pike, S., & Gupta, O. (2003). Towards the third generation of performance measurement. *Controlling, 3*(4), 129-135.

Neely, A., Mills, J., Platts, K., Richards, H., Gregory, M., Bourne, M., & Kennerley, M. (2000). Performance measurement system design: developing and testing a process-based approach. *International journal of operations & production management, 20*(10), 1119-1145.

Neely, A., Richards, H., Mills, J., Platts, K., & Bourne, M. (1997). Designing performance measures: a structured approach. *International journal of operations & production management*, *17*(11), 1131-1152.

Neely, A. D., Adams, C., & Kennerley, M. (2002). *The performance prism: The scorecard for measuring and managing business success*: Prentice Hall Financial Times London.

Neff, G., Fiore-Silfvast, B., & Dossick, C. S. (2010). A case study of the failure of digital communication to cross knowledge boundaries in virtual construction. *Information, Communication & Society*, *13*(4), 556-573.

Nepal, M. P., Jupp, J. R., & Aibinu, A. A. (2014). Evaluations of BIM: frameworks and perspectives. *Computing in Civil and Building Engineering (2014)*, 769-776.

Ngo, M. (2012). UK Construction Industry's responses to Government Construction Strategy BIM deadline and applications to civil engineering education.

NIBS. (2007). National Building Information Modeling Standard: Version 1.0- Part 1: Overview, Principles, and Methodologies.

NIBS. (2012). National BIM Standard- United States Version 2.

NIBS. (2015). National BIM Standard- United States Version 3.

Nudurupati, S. S., Bititci, U. S., Kumar, V., & Chan, F. T. S. (2011). State of the art literature review on performance measurement. *Computers & Industrial Engineering, 60*(2), 279-290. doi: http://dx.doi.org/10.1016/j.cie.2010.11.010

O'Dwyer, L. M., & Bernauer, J. A. (2013). *Quantitative research for the qualitative researcher*: Sage Publications.

Parker, C. (2000). Performance measurement. *Work study, 49*(2), 63-66.

Partidário, M. R. (1996). Strategic environmental assessment: Key issues emerging from recent practice. *Environmental impact assessment review, 16*(1), 31-55. doi: http://dx.doi.org/10.1016/0195-9255(95)00106-9

Paulk, M. (1993). *Capability maturity model for software*: Wiley Online Library.

Paulk, M. (2002). Capability Maturity Model for Software *Encyclopedia of Software Engineering*: John Wiley & Sons, Inc.

Paulk, M. C., Curtis, B., Chrissis, M. B., & Weber, C. V. (1993). Capability maturity model, version 1.1. *Software, IEEE, 10*(4), 18-27.

Paulk, M. C., Weber, C. V., Curtis, B., & Chrissis, M. B. (1994). *The capability maturity model: Guidelines for improving the software process* (Vol. 441): Addison-wesley Reading, MA.

Peters, K., & Halcomb, E. (2015). Interviews in qualitative research: A consideration of two very different issues in the use of interviews to collect research data. *Nurse researcher, 22*(4), 6-7.

Popov, V., Juocevicius, V., Migilinskas, D., Ustinovichius, L., & Mikalauskas, S. (2010). The use of a virtual building design and construction model for developing an effective project concept in 5D environment. *Automation in Construction, 19*(3), 357-367.

Pöppelbuß, J., & Röglinger, M. (2011). *What makes a useful maturity model? a framework of general design principles for maturity models and its demonstration in business process management.* Paper presented at the ECIS.

Powell, C. (2003). The Delphi technique: myths and realities. *Journal of advanced nursing, 41*(4), 376-382. doi: 10.1046/j.1365-2648.2003.02537.x

Race, S. (2012). *Bim Demystified*: Riba Enterprises.

Ragin, C. C. (1989). *The comparative method moving beyond qualitative and quantitative strategies*. Berkeley, CA: Berkeley, CA : University of California Press.

RIBA Enterprises. (2012). NBS National BIM Report 2012. Retrieved from: http://www.bimtaskgroup.org/wp-content/uploads/2012/03/NBS-NationalBIMReport12.pdf

RIBA Enterprises. (2013). NBS National BIM Report 2013. Retrieved from: http://www.thenbs.com/pdfs/NBS-International-BIM-Report_2013.pdf

RIBA Enterprises. (2014). NBS National BIM Report 2014. Retrieved from: http://www.thenbs.com/pdfs/NBS-National-BIM-Report-2014.pdf

RIBA Enterprises. (2015). NBS National BIM Report 2015. Retrieved from: http://www.thenbs.com/pdfs/NBS-National-BIM-Report-2015.pdf

RIBA Enterprises. (2016). NBS National BIM Report 2016. Retrieved from: http://www.thenbs.com/pdfs/NBS-National-BIM-Report-2015.pdf

Rihoux, B., & Ragin, C. C. (2008). *Configurational Comparative Methods Qualitative Comparative Analysis (QCA) and Related Techniques*. Los Angeles: Los Angeles : SAGE Publications Inc.

Ritchie, B. W., Burns, P. M., & Palmer, C. A. (2005). *Tourism research methods: integrating theory with practice*: Cabi.

Röglinger, M., Pöppelbuß, J., & Becker, J. (2012). Maturity models in business process management. *Business Process Management Journal, 18*(2), 328-346.

Sanchez, A. X., Mohamed, S., & Hampson, K. D. (2016). 4 BIM Benefits Realisation Management. *Delivering Value with BIM: A Whole-of-life Approach,* 58.

Saunders, M. N. (2011). *Research methods for business students, 5/e*: Pearson Education India.

Saunders, T. (2008). A discussion document comparing international environmental assessment methods for buildings. *BRE, March*.

Schweber, L. (2013). The effect of BREEAM on clients and construction professionals. *Building Research & Information, 41*(2), 129-145.

Schweber, L., & Haroglu, H. (2014). Comparing the fit between BREEAM assessment and design processes. *Building Research & Information, 42*(3).

Sebastian, R., & Berlo, L. (2010). Tool for benchmarking BIM performance of design, engineering and construction firms in the Netherlands. *Architectural Engineering and Design Management, 6*(4), 254-263.

Sharifi, A., & Murayama, A. (2013). A critical review of seven selected neighborhood sustainability assessment tools. *Environmental impact assessment review, 38*, 73-87. doi: http://dx.doi.org/10.1016/j.eiar.2012.06.006

Sharman, P., & Kavan, C. (1999). Software is not the solution: software selection’s effect on implementing the balanced scorecard. *Journal of Strategic Performance Measurement, 7*(3), 7-15.

Shepherd, P., & Richens, P. (2012). The case for subdivision surfaces in building design. *Journal of the International Association for Shell and Spatial Structures, 53*(174), 237-245.

Shin, J., Choi, J., & Kim, I. (2015a). Development of BIM Performance Measurement System for Architectural Design Firms *Computer-Aided Architectural Design Futures. The Next City-New Technologies and the Future of the Built Environment* (pp. 348-365): Springer.

Shin, J., Choi, J., & Kim, I. (2015b). A Study on BIM Performance Assessment Framework for Architecture Firm.

Singh, V., Gu, N., & Wang, X. (2011). A theoretical framework of a BIM-based multi-disciplinary collaboration platform. *Automation in Construction, 20*(2), 134-144.

Smeyers, P. (2001). Qualitative versus quantitative research design: A plea for paradigmatic tolerance in educational research. *Journal of philosophy of education, 35*(3), 477-495.

Succar, B. (2009a). Building information modelling framework: A research and delivery foundation for industry stakeholders. *Automation in Construction, 18*(3), 357-375. doi: http://dx.doi.org/10.1016/j.autcon.2008.10.003

Succar, B. (2009b). Building information modelling maturity matrix. *Handbook of Research on Building Information Modeling and Construction Informatics: Concepts and Technologies, IGI Global*, 65-103.

Succar, B. (2010a). Building information modelling maturity matrix. *Handbook of research on building information modelling and construction informatics: Concepts and technologies, J. Underwood and U. Isikdag, eds., IGI Publishing*, 65-103.

Succar, B. (2010b). *The five components of BIM performance measurement.* Paper presented at the Proceedings of CIB World Congress, Salford.

Succar, B. (2013). *Building Information Modelling: conceptual constructs and performance improvement tools.* Ph. D. Dissertation, School of Architecture and Built Environment Faculty of Engineering and Built Environment, University of Newcastle.

Succar, B., & Kassem, M. (2015). Macro-BIM adoption: Conceptual structures. *Automation in Construction, 57*, 64-79. doi: http://dx.doi.org/10.1016/j.autcon.2015.04.018

Succar, B., Sher, W., & Williams, A. (2012). Measuring BIM performance: Five metrics. *Architectural Engineering and Design Management, 8*(2), 120-142.

Succar, B., Sher, W., & Williams, A. (2013). An integrated approach to BIM competency assessment, acquisition and application. *Automation in Construction, 35*(0), 174-189. doi: http://dx.doi.org/10.1016/j.autcon.2013.05.016

Suchman, E. A. (1964). The Comparative Method In Social Research. *Rural Sociology, 29*(2), 123-138.

Tangen, S. (2004). Performance measurement: from philosophy to practice. *International Journal of Productivity and Performance Management, 53*(8), 726-737. doi: doi:10.1108/17410400410569134

Taticchi, P., Cocca, P., & Alberti, M. (2010). A framework to assess performance measurement systems in SMEs. *International Journal of Productivity and Performance Management, 59*(2), 186-200.

Team, C. P. (2010). *CMMI for Services Version 1.3*: Lulu. com.

Tellis, W. M. (1997). Application of a case study methodology. *The qualitative report, 3*(3), 1-19.

Thayer, R. H., Bailin, S. C., & Dorfman, M. (1997). *Software requirements engineerings*: IEEE Computer Society Press.

Todd, J. A., Crawley, D., Geissler, S., & Lindsey, G. (2001). Comparative assessment of environmental performance tools and the role of the Green Building Challenge. *Building Research & Information, 29*(5), 324-335.

UKAS. (2014). The United Kingdom Accreditation Service from http://www.ukas.com/about-accreditation/

VICO. (2011). Calculation your BIM score. Retrieved 26.02.2016, from http://www.vicosoftware.com/resources/calculating-bim-score/tabid/273811/Default.aspx

Volk, R., Stengel, J., & Schultmann, F. (2014). Building Information Modeling (BIM) for existing buildings—Literature review and future needs. *Automation in Construction, 38*, 109-127.

Wallhagen, M., & Glaumann, M. (2010). Design consequences of differences in building assessment tools: a case study. *Building Research & Information, 39*(1), 16-33. doi: 10.1080/09613218.2010.513210

Webster, J., & Watson, R. T. (2002). Analyzing the past to prepare for the future: Writing a literature review (pp. xiii-xxiii): JSTOR.

Wilson, V. (2012). Research Methods: Interviews. *Evidence Based Library and Information Practice, 7*(2), 96-98.

Won, J., & Lee, G. (2016). How to tell if a BIM project is successful: A goal-driven approach. *Automation in Construction, 69*, 34-43.

Woodside, A. G. (2010). *Case study research: Theory, methods and practice: Theory, methods, practice*: Emerald Group Publishing.

Wright, K. B. (2005). Researching Internet-based populations: Advantages and disadvantages of online survey research, online questionnaire authoring software packages, and web survey services. *Journal of Computer-Mediated Communication, 10*(3), 00-00.

Yan, H., & Damian, P. (2008). *Benefits and barriers of building information modelling.* Paper presented at the 12th International Conference on Computing in Civil and Building Engineering 2008.

Yin, R. K. (2003). *Case study research : design and methods* (3rd ed. ed.). Thousand Oaks, Calif.

Yin, R. K. (2011). *Applications of case study research*: Sage.

Yin, R. K. (2015). Case Studies A2 - Wright, James D *International Encyclopedia of the Social & Behavioral Sciences (Second Edition)* (pp. 194-201). Oxford: Elsevier.

Zeinal Hamedani, A., & Huber, F. (2012). *A comparative study of DGNB, LEED and BREEAM certificate systems in urban sustainability* M. Pacetti, G. Passerini, C. Brebbia, & G. Latini (Eds.), *The Sustainable City VII: Urban Regeneration and Sustainability*

Zhang, S., Teizer, J., Lee, J.-K., Eastman, C. M., & Venugopal, M. (2013). Building Information Modeling (BIM) and Safety: Automatic Safety Checking of Construction Models and Schedules. *Automation in Construction, 29*, 183-195. doi: http://dx.doi.org/10.1016/j.autcon.2012.05.006

Zhang, Y., & Wildemuth, B. (2009). Unstructured Interviews: The University of Texas at Austin.

Appendices

Appendix A. A paper at Integrated Design Conference at the University of Bath

THE EMERGENCE OF BUILDING INFORMATION MODELLING ASSESSMENT METHODS (BIM-AMs)

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ABSTRACT: Building Information Modelling Assessment Methods (BIM-AMs) are used to evaluate the implementation of BIM and improve its adoption in practice. Over the past nine years there have been at least 16 BIM-AMs developed in academia and industry, each offering a unique perspective on BIM performance. Despite the continual growth of BIM-AMs, the field as a whole is still under-examined. Most previous studies tend to focus only on introducing new methods, rather than comparing and contrasting the diverse range of existing models. This paper addresses this gap, by analysing the similarities and differences between these assessments. A critical evaluation of the current AMs covers several features, including their simplicity and complexity, the most evaluated measures, whether the AM assesses projects, organisations, teams or individuals and the forms of communication of the results. This is followed by a representation of limitations and roles of BIM-AMs. This comprehensive comparison enriches the current research agenda of BIM-AMs. It helps to collectively reflect the extensive body of knowledge on BIM-AMs and recommends directions for future research.

Keywords – BIM, Assessment Methods, performance measurement, maturity models, comparative method.

1. INTRODUCTION

In the last decade, the need for Building Information Modelling Assessment Methods (BIM-AMs) has rapidly increased. With the government BIM Level 2 target for all publicly-funded projects by 2016, and the enormous challenges in measuring the 'maturity' of BIM performance, it is of vital importance that professionals adopt BIM-AMs. Assessments help organisations to track their progression (CIC, 2013), create 'healthy feedback loop' of BIM capacity (Kam *et al.*, 2013b) and develop a roadmap for stakeholders to assist them identifying goals for their future plans (NIBS, 2007). These benefits have been highlighted by Neely *et al.* (1997), who work explicitly on the broader field of performance measurement:

> Businesses choose to measure performance for various reasons- to know where they are, to know how rapidly they are improving, to enable comparison with other businesses, even to influence individuals' behaviours (Neely *et al.*, 1997, p. 1141).

Since 2007, the research field of BIM performance measurement has witnessed a gradual growth with at least sixteen Assessment Methods (AMs) which evaluate projects, organisations, individuals and teams. Several universities and commercial companies in the Architecture, Engineering and Construction (AEC) domain have contributed to the field of BIM-AMs. Amongst the most recognisable assessments are the National BIM Standard Capability Maturity Model (NBIMS-CMM) (NIBS, 2007), which was the first AM developed, the BIM Maturity Matrix (Succar, 2010) and the Virtual Design and Construction (VDC) Scorecard (Kam, 2015). Each has a unique perspective on BIM performance.

Despite this increasing interest, there are many cultural and practical barriers to adopt BIM-AMs, which have prevented them becoming wide-spread. Such challenges include the shortage of frameworks that are ready for use in industry, the lack of case study projects for validation (Kam *et al.*, 2013b) and the absence of an overarching research agenda for BIM-AMs. Most existing academic literature has focused on individual AMs, rather than analysing the range of available AMs as a whole (CPI, 2011; VICO, 2011; CIC, 2013), which is crucial to understanding the full picture of BIM performance measurement. Neither common properties and shared characterisations, nor contrasting aspects of these AMs, have been considered previously (Indiana University Architect's Office, 2009; BRE, 2015). Only a handful of past studies, e.g. (Giel, 2013; NIBS, 2015), have consistently explored and examined the synthesis of multiple AMs. In particular, they focused on comparing the measures included in only six AMs by classifying them into five groups: planning, technical, personnel, managerial and process measures. What is needed to effectively understand the domain is to propose a research agenda for BIM-AMs by comprehensively presenting their current roles and future development. This paper, therefore, maps the landscape of BIM-AMs by exploring the literature in order to simplify the complexity of this research field.

1.1 Definitions of BIM-AMs

The literature on BIM-AMs presents a lack of consensus as to their definition and demonstrates the diversity of the subject. The earliest definition of BIM-AMs is reported by the National Institute of Building Sciences (NIBS), whose early AM, the Capability Maturity Model (CMM), is a tool targeted at the architecture, engineering, construction and operation industry for an immediate evaluation of current BIM processes in projects (NIBS, 2007). This evaluation is used by professionals to identify their current performance and create robust goals for future operations. BIM-AMs are also defined as 'instruments' that benchmark the *organisation's* BIM level of performance in the construction industry (Sebastian and Berlo, 2010). Each of the numerous definitions available in the literature is different, according to the authors' aim and perspective. Seemingly, the main difference between them is the assessment focus. In other words, some of the AMs assess projects others assess organisations, individuals or teams.

2. COMPARISON OF CURRENT BIM-AMS

The number of BIM performance measurement tools has gradually increased over the last decade (BRE, 2015; Nepal *et al.*, 2014; Succar, 2010). BIM-AMs have been developed in different countries, such as, the U.S. (7 AMs), the UK (3 AMs) and Australia (3 AMs). Table 1 presents the current AMs with main references according to their chronological progression. Development reached a peak in 2009 with four new assessments, and currently there are sixteen known BIM-AMs. Each of them, however, has different strengths, weaknesses, roles and emphasis. Some of the AMs, for instance, are user-friendly (Arup, 2014), provide guidelines for usage, are available free on-line (CIC, 2013) and offer case study projects (Berlo *et al.*, 2012). Others are less practical, lack instructions or require an external examiner and fees to implement the assessment (BRE, 2015), or suffer from a shortage of case study projects (VICO, 2011).

To support an understanding of the generic development of BIM-AMs, critical analysis of the literature has been carried out to compare their diverse properties. This comparison plays a central role in concept-formation, as it examines similar and contrasting features among different cases (Collier, 1993). Some of the distinguishing properties addressed in this paper are the origins of AMs, year of development, the simplicity and complexity, the most evaluated measures, whether the AM assesses projects, organisations, teams or individuals and the forms of results' communication.

Table 1 Existing BIM-AMs

Order	BIM-AM	Year	Main Reference
1	NBIMS-CMM	2007	(NIBS, 2007)
2	BIM Excellence	2009	(Change Agents AEC, 2013)
3	BIM Proficiency Matrix	2009	(Indiana University Architect's Office, 2009)
4	BIM Maturity Matrix	2009	(Succar, 2010)
5	BIM Quick Scan	2009	(Sebastian and Berlo, 2010)
6	VICO BIM Score	2011	(VICO, 2011)
7	Characterisation Framework	2011	(Gao, 2011)
8	CPIx BIM Assessment Form	2011	(CPI, 2011)
9	Organisational BIM Assessment Profile	2012	(CIC, 2013)
10	VDC Scorecard	2012	(Kam *et al.*, 2013b, a; Kam, 2015)
11	bim Score	2013	(bimSCORE, 2013)
12	The Owner's BIMCAT	2013	(Giel, 2013)
13	BIM Maturity Measure	2014	(Arup, 2014)
14	Goal-driven method for evaluation of BIM project	2014	(Lee and Won, 2014)
15	The TOPC evaluation criteria	2014	(Nepal *et al.*, 2014)
16	BIM Level 2 BRE Certification	2015	(BRE, 2015)

2.1 Simplicity versus complexity

AMs are generally designed to reflect either a model simplicity or a complex reality. Each has its own advantages and disadvantages (De Bruin *et al.*, 2005). The level of simplicity and complexity is dependent on the numbers and type of evaluated measures. Oversimplified AMs tend to be short, attracting more interest as they require less time to complete. However, they may not represent the complexity of the domain if they are limited to specific areas of BIM. Half of the current AMs evaluate fewer than thirty measures (sometimes called indicators, variables or areas of interest), as illustrated in Figure 1. The NBIMS-CMM is an example of a simplified AM (NIBS, 2007), with only 11 measures. Participants completing the NBIMS-CMM are required to answer 11 questions, which takes 15-30 minutes to complete. Critics of NBIMS-CMM contend that this AM is limited to specific measures and does not benchmark diverse areas of BIM (Kam *et al.*, 2013b). In contrast, complex AMs are always more detailed and comprehensive than the simplified models. The largest number of measures can be found in the 'Characterisation Framework' with 74 measures, over six times the number evaluated in NBIMS-CMM (Gao, 2011). This is followed by the 'Owner's BIMCAT', which includes 66 measures (Giel, 2013). However, one criticism in much of the literature on complex AMs is that they limit interest, (De Bruin *et al.*, 2005), because of their extensive detail and the time needed to complete the assessment. Difficulties arise when an attempt is made to complete the full detailed assessment and respondents might leave many questions unanswered. For instance, when the Centre of Integrated Facility Engineering (CIFE) researchers evaluated 108 pilot projects using the VDC Scorecard, the average proportion of questions answered was 72% (Kam *et al.*, 2013b). The link between simplicity and complexity is dynamic. Thereby, simplicity might be found in 'complex' AMs when a detailed method employs clear language, description of the measures and a structured framework with direct guidelines on how to use this AM. It is also found that simplified and short tools might be difficult to apply if they lack clear structure.

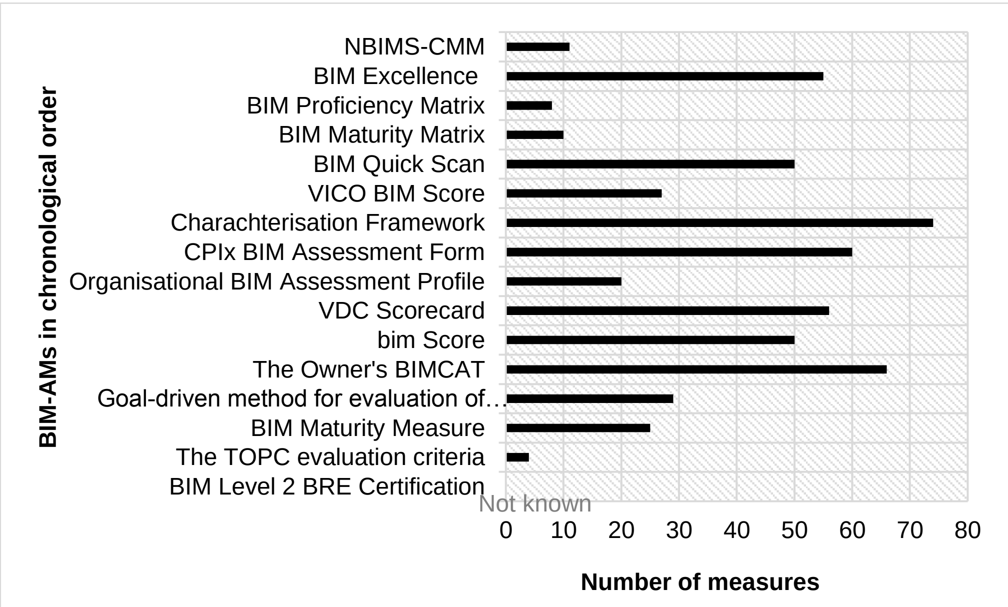

Figure 1 Simplicity versus complexity of the current BIM-AMs (from older, NBIMS-CMM, to most recent BRE Certification)

2.3 Assessment focus

BIM-AMs can be classified into four different groups according to their evaluation focus. AMs can evaluate BIM across either projects, organisations, teams or individuals. Currently, ten of the sixteen AMs evaluate organisations compared to six evaluate BIM in projects, three across individuals and one across teams. Some of the existing AMs, however, have multiple versions in which each has a different evaluation focus. The most recent BIM-AM, for instance, the 'BIM Level2 BRE Certification' has two versions (BRE, 2015): 'BIM Level 2 Business Systems Certification', evaluates organisations, and 'BIM Level 2 Certificated Practitioner Scheme', which assesses individuals.

Each of the four groups has its main focus. AMs of 'organisations' help the AEC industry to assess their readiness practices when implementing BIM (CIC, 2013). AMs that evaluate 'projects' help companies to manage their BIM utilisation. They assist managers in minimising uncertainty and concentrating financial and human resources on critical issues (Kam, 2015). Assessing 'projects' was first suggested in 2007 when NBIMS-CMM was created (NIBS, 2007). Whilst wider efforts have been given to evaluating organisations and projects, far less attention has been directed at assessing teams and individuals. In fact, it might be a challenge to evaluate individuals and teams in terms of BIM. One of the main concerns is the continuity of the BIM experience. If recognition was given to individuals at a certain time, would there be an expiry date of this credit, or would they need to be assessed again to check that their BIM knowledge and expertise has been maintained? Future direction of individual assessments might therefore suggest a continuous evaluation to ensure those certified professionals still meet the appropriate requirements.

The AMs of organisations and projects are different in their objectives and therefore they define different areas of measurement. The former tends to focus on assessing visions, plans, culture change, collaboration and strategies of BIM in organisations. Thus, AMs of organisations provide feedback on the organisation scale, without necessarily assessing any of its individual projects. Project assessment, however, is more concerned with evaluating how BIM has been implemented in terms of, for instance, data richness, data exchange and model use. Each project is unique, and therefore, levels of BIM implementation will vary within the same organisation according to certain circumstances, such as project size, complexity and client requirement.

2.2 Range of BIM-AMs' measures

Choosing specific measures to benchmark is a fundamental part of the development of a performance measurement system in any discipline (Hatry, 2006). Each of the current BIM-AMs has its unique list of measures based on its objectives and priorities. Some of these measures are qualitative, and others are quantitative. The array of evaluated criteria is vast with over 200 different measures across the 16 AMs. To further complicate the situation, several developers evaluated the same measure, but used different terminologies. Therefore, in order to investigate the most popular evaluated measures, all have been extracted and classified into groups which evaluate the same BIM area. The most popular five measures, in order, are data richness, visions and goals, technology, data exchange and model use (Table 2).

Data richness is the highest examined measure and is therefore particularly important to scholars in the field of BIM performance measurement. It refers to 'the maximum amount of information and geometry authorised for use by others' (Harvard UCMC, 2013, p. 12). Eight of the AMs evaluate it, but they use different terms such as 'Level of Detail' (LOD) and 'level of development' (see Table 2). This includes the geometrical and non-geometrical information which an organisation needs to complete a specific BIM task at a certain timeframe. One of the big questions is how to measure LOD accurately without relying on subjective evaluation. Even with the five LODs defined by American Institute of Architects (AIA, 2008), it is still challenging to define sharp boundaries between these levels.

Table 2 Most commonly evaluated measures across the 16 BIM-AMs, with exact terminology

BIM-AM	**Data richness**	**Visions and goals**	**Technology**	**Data exchange**	**Model use**
NBIMS-CMM	Data richness	-	-	Interoperability + Delivery Method	-
BIM Excellence	-	-	Technical	-	-
BIM Proficiency Matrix	Data richness	-	-	-	-
BIM Maturity Matrix	-	Leaderships' BIM visions	Technology	Network	Software usage
BIM Quick Scan	-	Vision &strategy	Tools and applications	Internal and external information flow	Use of modelling
VICO BIM Score	-	-	-	-	-
Characterisation Framework	Level of detail	Vision into Implementing BIM		Data Exchange	Model Uses
CPIx BIM Assessment Form	-	-	-	-	-
Organisational BIM Assessment Profile	Level of development	BIM vision & Objectives/ goals	Software and hardware	-	-
VDC Scorecard	Level of detail/ development	Management Objectives	Technology	Data Sharing Method	Model uses
bim Score	Level of detail/ development	Management Objectives	Technology	Data Sharing Method	Model uses
The Owner's BIMCAT	Data richness/ LOD	Goals/ Objectives	Technology	-	-
BIM Maturity Measure	Level of development	-	-	Common data environment	Drawings
Goal-driven method for evaluation of BIM project	-	-	-	-	-
The TOPC evaluation criteria	-	-	-	-	-
BIM Level 2 BRE Certification	Not known				
Total number of AMs measuring this	8	7	7	7	6

The second joint most common measures are ‘visions and goals’, ‘technology’ and ‘data exchange’ examined in seven AMs. Similar to LOD, these measures are interpreted differently as seen in Table 2. On the practical side, the measures will be evaluated against various levels of maturity. For instance, in the ‘Organisational BIM Assessment Profile’, participants have to select one out of six maturity measures ranging from *0 Non-Existent* (no BIM vision of objectives defined) to *5 Optimising (CIC, 2013)*.

One of the main challenges when investigating the range of measures is to classify them into useful and structured categories. Past researchers have differently categorised measures into main BIM areas and sub-areas. Defining key common measures across the 16 AMs is still problematic. Many scholars have not clearly defined or explained their measures, making it difficult to explore similarities and differences. Another unresolved problem is deciding what type of performance information should be tracked. Several developers of the existing AMs have extensively discussed the methodological criteria behind selecting their measures. This includes explanations of employed methods in the development of AMs such as Delphi method, focus groups and surveys. In contrast, it is not clear in many other AMs how the measures have been chosen (CPI, 2011; VICO, 2011).

2.4 Reporting results

Clearly communicating the results of an AM is crucial to understanding the meaning of the outcomes. In the current BIM-AMs, results are presented in several forms including radar charts (Sebastian and Berlo, 2010; Arup, 2014), tables (Indiana University Architect's Office, 2009), reports (Change Agents AEC, 2013) and certifications (BRE, 2015), see Figure 2. A final overall score is usually provided either as a percentage or as points. In several AMs, once the overall score of the assessment is calculated, it will be then allocated to one of multiple ‘BIM Maturity Levels’. For example, in the VDC Scorecard, an overall score will be allocated to one out of five maturity levels ranging from Conventional Practice (0-25%) to Innovative Practice (90-100%) as seen in Figure 2. Other AMs similarly calculate the overall score, but without allocating the project to a certain level of maturity. This is exemplified in the BIM Maturity Measure (BIM-MM) developed by Arup (Arup, 2014) where, once the assessment is completed, a primary score is provided as a percentage, but without being directed to a particular maturity level.

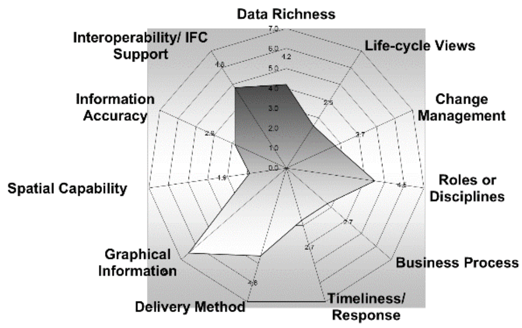

Figure 2 Communicating results in VDC Scorecard (Left), (Kam et al., 2013b), and NBIMS-CMM (right), (NIBS, 2007)

3. BIM-AMs: limitations and roles

Having discussed the different properties of BIM-AMs, it is beneficial to collectively provide a snapshot of their evolution and the emerging trends. This snapshot is portrayed in Figure 3 which demonstrates the development of AMs between 2007 and 2016. It also presents their diverse features, explained previously, which include year of development, origin, whether they are research or industry based, their complexity and whether they evaluate projects, organisations, teams or individuals. Previous advances in AMs have contributed significantly to the field of BIM performance measurement. This contribution varies, however, according to the limitations and roles of each assessment.

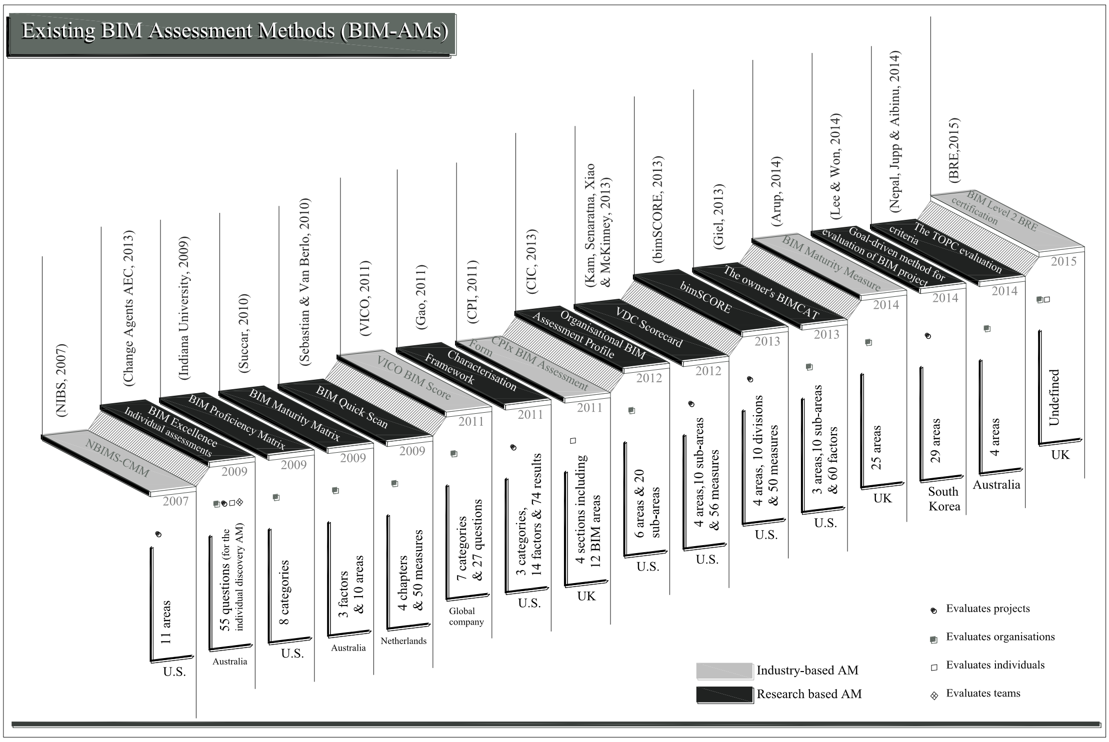

Figure 3 The evolution of BIM-AMs

3.1 Limitations of current BIM-AMs

There are many limitations facing the existing BIM-AMs, and the most important four are presented here. Firstly, most current AMs lack quantitative and objective measures when evaluating BIM. This makes subjectivity one of the most pressing challenges in BIM performance measurement (Kam, 2013). For example, some of the evaluated measures in NBIMS-CMM, business process and data richness, are subjective and open to interpretation. Consequently, it is likely that scores might be different when the AM is completed by two participants evaluating the same project (NIBS, 2007). Secondly, there are limited case study projects supporting the validation process of AMs (Kam *et al.*, 2013b). Thirdly, none of the current AMs have been widely acknowledged and commonly applied in the AEC industry (Sebastian and Berlo, 2010). In contrast, many AMs in different disciplines are well recognised, such as BREEAM and LEED. Fourthly, the criteria for selecting and weighting the measures in some of the AMs is not clear. For instance, the release of 'BIM Level 2 Business Systems Certifications' and 'VICO BIM Score' have not been supported by any explanation of their development process. In order to overcome these limitations, future AMs should build on the previous work to learn lessons and avoid current problems. AMs have to have more quantitative measures because subjectivity is one of the most inherent challenges. In addition, more case study projects should be provided which would assist in exploring the validation, practicality and reliability of tested AMs.

3.2 Role of current BIM-AMs

Despite their various limitations, AMs have become wide-spread in different fields such as environmental sciences, computer science, business and management. This significance can be linked to their roles and the impact on these disciplines. Neely (1999) identifies seven reasons for the 'revolution' of performance measurement, including the changing nature of work, increasing competition, changing organisational roles, changing external demands and the power of information technology. These reasons can equally be applied to the AEC industry and might explain the growth in the field of BIM-AMs. According to previous researchers, BIM-AMs have numerous roles, including the ability to:

- Help academia and industry to distinguish a 'healthy feedback loop' of BIM capacity in practice. This feedback may assist professionals to optimise their BIM adoption and increase their return on investment (Kam *et al.*, 2013b, p. 4)
- Assist companies to evaluate their level of BIM integration and improve their current adoption by defining advancement strategies and objectives (CIC, 2013)
- Document BIM implementation of previous projects as an internal source of information. This documentation may help BIM managers to compare projects to each other and increase BIM benefits (Gao, 2011)
- Help companies to compare projects, both internally and externally, in order to optimise their performance. This would provide an overall review of the industry's performance when trends in industry surveys are observed (McCuen *et al.*, 2012)
- Develop a roadmap for stakeholders to help them identify goals for future plans (NIBS, 2007)
- Help companies gain market recognition for their BIM services when high levels of maturity are achieved (Succar, 2010)

BIM-AMs offer opportunities for improvement by identifying areas of strengths and weaknesses. At the decision makers' level, the results of BIM-AMs provide governments and local authorities with a better understanding of the current position of BIM implementation. At the company level, professionals can use the results to compare capabilities between different projects and teams internally. Finally, for individual and team assessments, the results help companies to optimise their staff performance and influence individuals to improve their implementation of BIM (including training and education).

4. CONCLUSION

This paper has explored the current state-of-the-art in the field of BIM-AMs. The main focus has been to provide a comparative analysis of the AMs by contrasting a number of their distinguishing characteristics. From this comparison, a number of conclusions can be drawn. Firstly, over the past decade, the number of BIM-AMs has seen a gradual growth, both in academia and in the AEC industry. This growing interest reflects the need for AMs to help professionals achieve sharper and more efficient businesses by identifying areas of limitations and potential optimisations. Secondly, it is clear that each AM has its unique properties, aims and evaluation criteria, with widely varied number and type of measures. Thirdly, in order to shift BIM-AMs from theory into a broader practical context, their roles, contributions and significance should be acknowledged. Indeed, one of their indirect contributions is the ability to encourage a dialogue and a greater level of communication between different individuals and teams. If applied at the early stages of a project, BIM-AMs have the potential to introduce an array of BIM-related measures. Such measures will create a common language and set shared goals for individuals to achieve by the end of the project. This particular benefit of AMs has not yet been debated in the BIM literature, but has been highlighted in other fields, such as the environmental AMs.

The next steps for BIM-AMs should focus on both awareness and improvement. Awareness should be raised of the importance of measurement as a source of power and innovation. This should be done at three levels: academia (for more research to be carried out), AEC industry (to apply AMs in practical context) and Government (to benchmark the implementation of BIM on a national level). Improving on the current shortcomings of BIM-AMs, especially the subjectivity of its measures, is also of great importance. AMs offer opportunities for the future, but the research field of BIM-AMs is in its infancy and much more work needs to be done.

REFERENCES

AIA, A., 2008. Document E202-2008. *Building Information Modeling Protocol Exhibit, Washington, DC: American Institute of Architects*.

Arup, 2014. *The BIM Matuity Measure model* [Online]. Arup. Available from: http://www.arup.com/Services/Building_Modelling.aspx [Accessed 26.02.2016].

Berlo, L., Dijkmans, T., Hendriks, H., Spekkink, D. & Pel, W., 2012. BIM quickscan: benchmark of BIM performance in the Netherlands. *CIB W78*.

bimSCORE, 2013. *bimSCORE* [Online]. Available from: https://www.bimscore.com/index.php/welcome [Accessed 26.02.2016].

BRE, 2015. *BIM Level 2 Business Systems Certification* [Online]. Available from: http://www.bre.co.uk/page.jsp?id=3389 [Accessed 26.02.2016].

Change Agents AEC, 2013. BIM Excellence Performance Measurement Coporate Services

CIC, 2013. BIM Planning Guide for Facility Owners. Version 2.0. Available: http://bim.psu.edu/.

Collier, D., 1993. The comparative method. *Political Science: The State of Discipline II, Ada W. Finifter, ed., American Political Science Association*.

CPI, 2011. CPIx-BIM Assessment Form.

De Bruin, T., Freeze, R., Kaulkarni, U. & Rosemann, M., 2005. Understanding the main phases of developing a maturity assessment model.

Gao, J., 2011. *A Characterization Framework to Document and Compare BIM Implementations on Construction Projects.* Stanford University.

Giel, B.K., 2013. *Framework for Evaluating the BIM Competencies of Building Owners.* [Gainesville, Fla: University of Florida.

Harvard UCMC, 2013. *Getting started with Building Information Modelling.* Harvard University.

Hatry, H.P., 2006. *Performance measurement: Getting results.* The Urban Insitute.

Indiana University Architect's Office, 2009. Building Information Modeling (BIM) Guidelines and Standards for Architects, Engineers, and Contractors.

Kam, C., 2013. Using Objectified Measures to Realize the Promise of BIM *Journal of the National Institute of Building Sciences (US) publication*.

Kam, C., 2015. Managing BIM Projects, Organizations, and Policies: Turning Aspirations into Quantitative Measures of Success. *Building Information Modeling: BIM in Current and Future Practice*, pp. 267-280.

Kam, C., Senaratna, D., Xiao, Y. & McKinney, B., 2013a. The VDC Scorecard: Evaluation of AEC Projects and Industry Trends.

Kam, C., Senaratna, D., Xiao, Y. & McKinney, B., 2013b. The VDC Scorecard: Formulation, Application and Validation. *Stanford University*.

Lee, G. & Won, J., 2014. Goal-driven method for sustainable evaluation of BIM project. In: A. Mahdavi & B. Martens, eds. *European Conference on Product and Process Modelling (ECPPM).* VIenna, Austria taylor & Francis

McCuen, T.L., Suermann, P.C. & Krogulecki, M.J., 2012. Evaluating Award-Winning BIM Projects Using the National Building Information Model Standard Capability Maturity Model. *Journal of Management in Engineering,* 28(2), pp. 224-230.

Neely, A., 1999. The performance measurement revolution: why now and what next? *International journal of operations & production management,* 19(2), pp. 205-228.

Neely, A., Richards, H., Mills, J., Platts, K. & Bourne, M., 1997. Designing performance measures: a structured approach. *International journal of operations & Production management,* 17(11), pp. 1131-1152.

Nepal, M.P., Jupp, J.R. & Aibinu, A.A., 2014. Evaluations of BIM: frameworks and perspectives. *Computing in Civil and Building Engineering (2014)*, pp. 769-776.

NIBS, 2007. National Building Information Modeling Standard: Version 1.0- Part 1: Overview, Principles, and Methodologies.

NIBS, 2015. National BIM Standard- United States Version 3.

Sebastian, R. & Berlo, L., 2010. Tool for benchmarking BIM performance of design, engineering and construction firms in the Netherlands. *Architectural Engineering and Design Management,* 6(4), pp. 254-263.

Succar, B., 2010. Building information modelling maturity matrix. *Handbook of research on building information modelling and construction informatics: Concepts and technologies, J. Underwood and U. Isikdag, eds., IGI Publishing*, pp. 65-103.

VICO, 2011. *Calculation your BIM score* [Online]. Available from: http://www.vicosoftware.com/resources/calculating-bim-score/tabid/273811/Default.aspx [Accessed 26.02.2016].

Appendix B. A paper at ARCOM Conference

Using the Arup BIM Maturity Measure to demonstrate BIM implementation in practice

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Abstract

Building Information Modelling Assessment Methods (BIM-AMs) are performance measurement systems that evaluate BIM across organisations, projects, individuals and teams. They focus priorities and help companies communicate their strategies both internally within their own businesses, and externally to other stakeholders. Currently, there are sixteen known assessments and each has its unique take on performance measurement. Amongst these models is the recently released BIM Maturity Measure (BIM-MM) which integrates critical elements of BIM including the BIM Champion, Common Data Environment and Employers Information Requirements. In this study BIM-MM is applied to 213 projects, in association with Arup, a global firm of consulting engineers. The aim of this substantial test is not only to investigate the implementation of BIM-MM in practice but more significantly to shed light on how BIM is being used in practice. In particular, the emphasis is on the relationship between the BIM Champion and the rest of the evaluated measures. Observations show that the overall scores of all projects is higher when the BIM Champion has a greater level of involvement in projects. BIM-AMs are of vital importance for policy-makers, professionals and researchers since they illustrate a broad snapshot of BIM adoption between and across organisations and countries. They are critical to the future directions of BIM agenda.

Keywords: BIM, Assessment Methods, BIM Maturity Measure, BIM champion

INTRODUCTION

In the last decade, the development of Building Information Modelling Assessment Methods (BIM-AMs) has been the subject of significant research (BRE, 2015; Giel, 2013; Kam, 2015; Succar et al., 2012). This development has led to sixteen Assessment Methods (AMs) introduced by both academics and practitioners. Each AM provides a unique perspective on BIM performance, with different sets of measures and different assessment focus. The first AM was the National BIM Standard Capability Maturity Model (NBIMS-CMM), developed in the U.S. by the National Institute of Building Sciences (NIBS, 2007). NBIMS-CMM consists of eleven critical BIM measures, including business process, delivery method, data richness and information accuracy. It focuses only on information management and has been therefore criticised for not reflecting the diverse facets of BIM. Critics have also questioned its usefulness and usability due to its structural limitations (Succar, 2010). So profound and powerful these critics were and resulted in the introduction of new models that tried to build on NBIM-CMM and provide more optimised models.

The emergence of new BIM-AMs was seeking better ways of measuring BIM. Frameworks such as the BIM Maturity Matrix (Succar, 2010), the Virtual Design and Construction (VDC) Scorecard

(Kam, 2015) and the BIM Maturity Measure (BIM-MM) (Arup, 2014), have been designed to improve previous models. They have supplemented past measures with diverse areas of measurement that represent much broader dimensions of BIM e.g. policies, technologies and processes. Individually and collectively, coexisting AMs have contributed to the growing body of literature that examines BIM use. Despite this growth, the research field of BIM-AMs as a whole is still facing fundamental challenges. Until recently, there has been a lack of knowledge surrounding the 'implementation' of many assessments in practice. This is essential to shift the field of BIM-AMs from its theoretical basis into an effective and practical context, a challenge documented previously by Neely et al. (2000) who write extensively on performance measurement:

> "The process of designing a measurement system is intellectually challenging, fulfilling and immensely valuable to those managers who participate fully in it….[However,] the real challenges for managers come once they have developed their robust measurement system, for then they must implement the measures."

This gap in literature is addressed here by implementing the Arup BIM-MM on a substantial dataset of 213 projects. The study considers the BIM-MM as an analytical framework and questions its ability to specify how BIM is being implemented across projects. Arup released the BIM-MM in December 2014 to assess and compare the maturity of BIM implementation within projects. It draws on the Organisational BIM Assessment Profile (CIC, 2013) under the Creative Commons 3.0 licence (Arup, 2014). This testing is important for professionals to review their progress over time, for academics to address the current challenges and opportunities of AMs and for policy-makers to create an overall picture of BIM implementation on a national scale.

LITERATURE REVIEW: BIM-AMs

Initial development of BIM evaluation systems is originally rooted in the software engineering Capability Maturity Model (CMM) which informed the first BIM-AM, the NBIMS-CMM (NIBS, 2007). Since then, multiple conflicting models have emerged shaped by both external and internal influences. Externally, AMs have been informed by the broader performance measurement systems in different fields, including business management, quality management and building environmental AMs. Internally, more recent BIM-AMs have built upon previous ones to avoid shortcomings. Together, these influences have impacted on the evolution of BIM-AMs in regard to the design process, type and range of measures and the ways results are communicated.

The significance and need for BIM-AMs has been highlighted by various scholars. A study by Succar et al. (2012) introduced three core advantages of BIM performance metrics. Such metrics enable teams and organisations to benchmark their own successes and (or) failures, evaluate their own BIM competencies and compare their progress against different companies in the Architecture Engineering and Construction (AEC) industry. Similarly, researchers in the 'Computer Integrated Construction (CIC) research programme' (2013), note that assessments help companies; internally to identify their current status, and externally to determine where they stand within the business market. Despite these advantages, there is still a shortage of literature which examines AMs in practice.

Most studies on BIM-AMs have focused on introducing and promoting new models, rather than implementing them in the architecture, engineering and construction industry. In the reviewed literature, publications of Case Study Projects (CSPs) is only available on seven AMs. For instance, the 'BIM Proficiency Matrix' (Indiana University Architect's Office, 2009) and the 'Organisational BIM Assessment Profile' (CIC, 2013) have contributed significantly to the field of BIM performance measurement, but no available publications document their implementation in practice. Table 1 presents all existing assessments according to their chronological order and reports the number of available CSPs.

Table 1 Availability of case study projects across the existing BIM-AMs

BIM-AM	Year developed	Origin	No of CSPs	Reference
NBIMS-CMM	2007	U.S.	11	(McCuen et al., 2012)
BIM Excellence	2009	Australia	-	(Change Agents AEC, 2013)
BIM Proficiency Matrix	2009	U.S.	-	(Indiana University Architect's Office, 2009)
BIM Maturity Matrix	2009	Australia	-	
BIM Quickscan	2009	The Netherlands	130	(Berlo et al., 2012)
VICO BIM Score	2011	Global company	-	
Characterisation Framework	2011	U.S.	40	(Gao, 2011)
CPIx BIM Assessment Form	2011	UK	-	
Organisational BIM Assessment Profile	2012	U.S.	-	
VDC Scorecard/bimSCORE	2012	U.S.	130	(Kam, 2015)
Owner's BIMCAT	2013	U.S.	2	(Giel, 2013)
BIM-MM	2014	**UK**	**213**	**(Arup, 2014)**
Goal-driven method for evaluation of BIM project	2014	South Korea	2	(Lee & Won, 2014)
The TOPC evaluation criteria	2014	Australia	-	
BIM Level 2 BRE certification	2015	UK	-	

As seen in Table 1 above there are sixteen models developed in different countries. The advantages and disadvantages of these models vary greatly. For instance, the BIM-MM is currently the only UK-based AM that evaluates the BIM maturity of 'projects'. It seeks greater linkages between substantial measures that reflect the broader perspectives of BIM, rather than focusing on one area, as in the NBIMS-CMM. It is a self-assessment and freely available for wider industry use, whilst in the BRE certifications a third-party is required to complete the assessment, which incurs a fee. Furthermore, BIM-MM is user-friendly and short to complete which attracts more interest compared to models that are detailed and complex. However, in order to optimise the BIM-MM, it should be implemented in practice which would maximise its effectiveness and suggest future directions of model to evolve.

RESEARCH METHODS

A comprehensive study is reported in this paper which documents the implementation of BIM-MM on 213 CSPs at Arup. The purpose of this AM is to enable comparison between projects, demystify BIM and to improve its capabilities across design and engineering disciplines (Arup, 2014). BIM-MM consists of eight parts: project, structural, mechanical, electrical, public health, facades, geotechnics and lighting. To complete the assessment participants have to specify one out of six possible maturity levels for each of the evaluated measures. These levels are 0 Non-Existent, 1 Initial, 2 Managed, 3 Defined, 4 Measured and 5 Optimising.

Once project assessment is completed (the first part of the BIM-MM) an overall 'Information Management Score' (IM Score) is provided. In addition, a "Primary Score", gives the average scores of the Project and the first four disciplines, usually Structures, Mechanical, Electrical and Public

Health. The ideal scenario is to complete all seven parts of the BIM-MM to provide a holistic portrait of BIM implementation across project teams. However, projects can still be assessed based only on the project part and at least one of the eight other disciplines.

Data collection and analysis

Data collection was carried out by different project teams within Arup. The BIM-MM was advertised internally in Arup's offices for self-assessment use. This was supplemented with training videos, documentation and workshops to guide and encourage the use of the tool around the world. Then, individual teams identified appropriate BIM projects for examination. The project manager of each team ensured the completion of the assessment, either by carrying it out themselves, or by handing it to someone within the team. In both cases, different project members might be consulted to get more information needed for the test.

To analyse the results of the 213 projects, the comparative method was used. The comparative method is a fundamental tool of analysis, since it sharpens the power of description and focus similarities and differences across CSPs (Collier, 1993). Unlike 'case study' approach, comparative method does not provide highly contextualised and rich emphasis of individual CSP. Instead, it aims to identify "clusters of elements or configurations that support particular outcomes" (Schweber & Haroglu, 2014). It also assists in identifying the distinctive connections, trends and patterns when comparing processes and relationships across cases (Ragin, 1989).

FINDINGS: APPLICATION OF BIM-MM

Analysis of the 213, exhibited in Figure 1, provides an overarching view of how BIM is being implemented across some critical measures. The figure shows the distribution of these projects through the six levels of maturity. In particular, it focuses on the first part of the BIM-MM, namely, the 'Project BIM Maturity' section, which consists of eleven measures. As seen in Figure 1, the numbers of projects with low levels of maturity (level 0 Non-Existent, level 1 Initial and level 2 Managed) is higher than the number of projects with high levels of maturity (level 4 Managed and level 5 Optimising). Examples can be found in six measures i.e. BIM Design Data Review, Project Procurement Route, Marketing Strategy, Open Standard Deliverables, BIM Contract and BIM Champion, in which all have fewer projects with higher levels of maturity. For instance, in Project Procurement Route, the number of projects allocated to level 5 Optimising is over five times fewer than projects with level 0 Non-Existent (7% and 39% respectively).

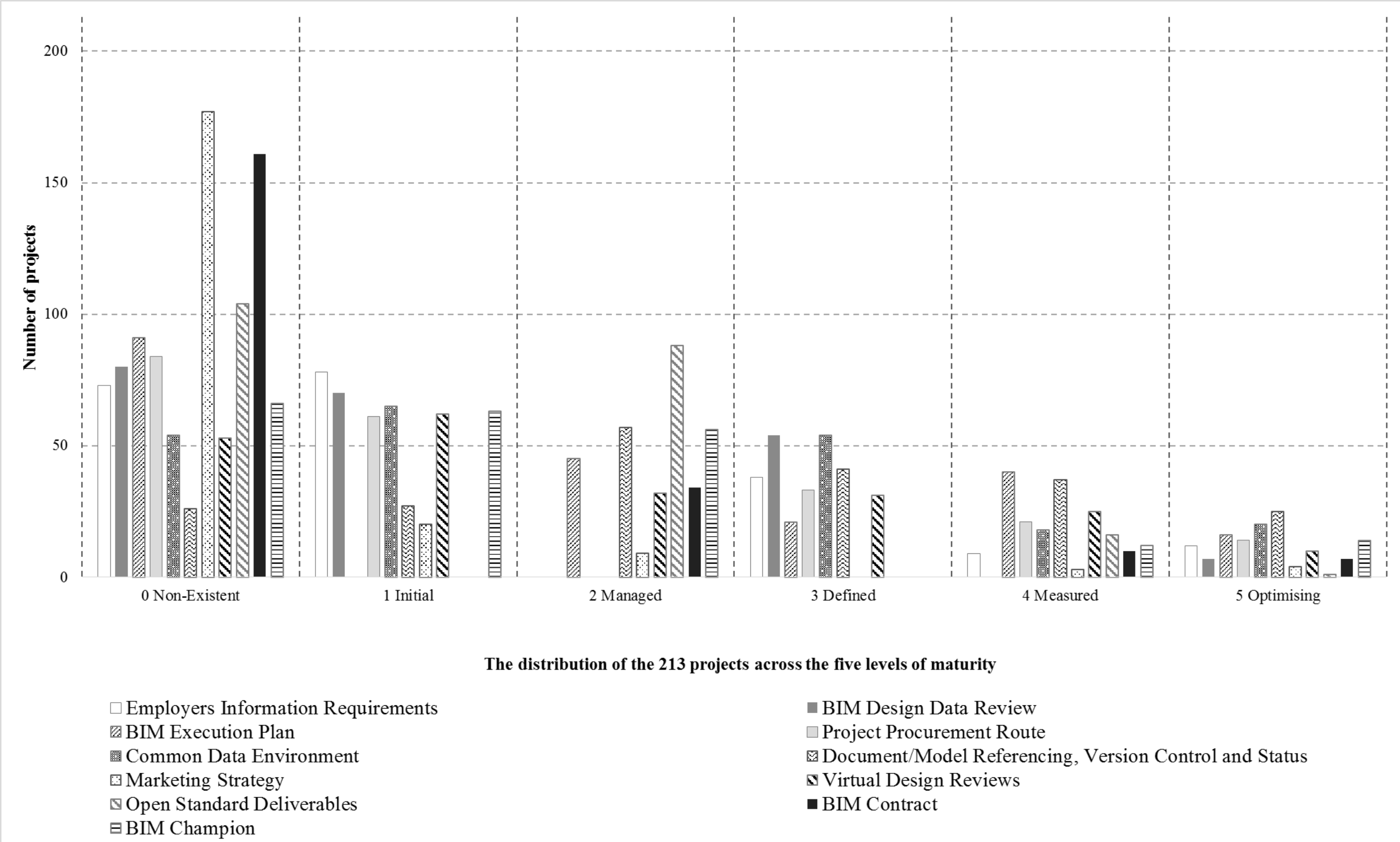

Figure 1 The performance of 213 case study projects against the five levels of maturity across the eleven measures

The mapping of these projects enables specific areas of strengths and weaknesses to be identified. Three quarters of all the 213 projects (76%) have no BIM contract or provide poorly-defined BIM agreements in consultant appointment (top left of Figure 2). As a result, the company could explore the impact of this factor on their business. If the absence of a contract reduces the potential benefits of BIM, then all parties, including contractors, should sign up to an industry standard BIM contract. Similarly, high numbers of projects have no Marketing Strategy (83%), defined by the BIM-MM as ‘BIM specific case studies to showcase and share the key points’. Whilst the lack of marketing strategy will not necessarily have a negative influence on the adoption of BIM, nevertheless the act of engaging with this AM has identified a potential area for development which might otherwise have been missed. Strengths can also be identified. In the ‘BIM Execution Plan’ (BEP) measure, 57% of the projects range between level ‘2 Managed’ to level ‘5 Optimising’, which means that BEPs have been used in all these projects to formalise goals and specify information exchange. Another example of strength is found in Document and Model Referencing, Version Control and Status with 75% of projects ranging between level ‘2 Managed’ to level ‘5 Optimising’ (bottom left of Figure 2).

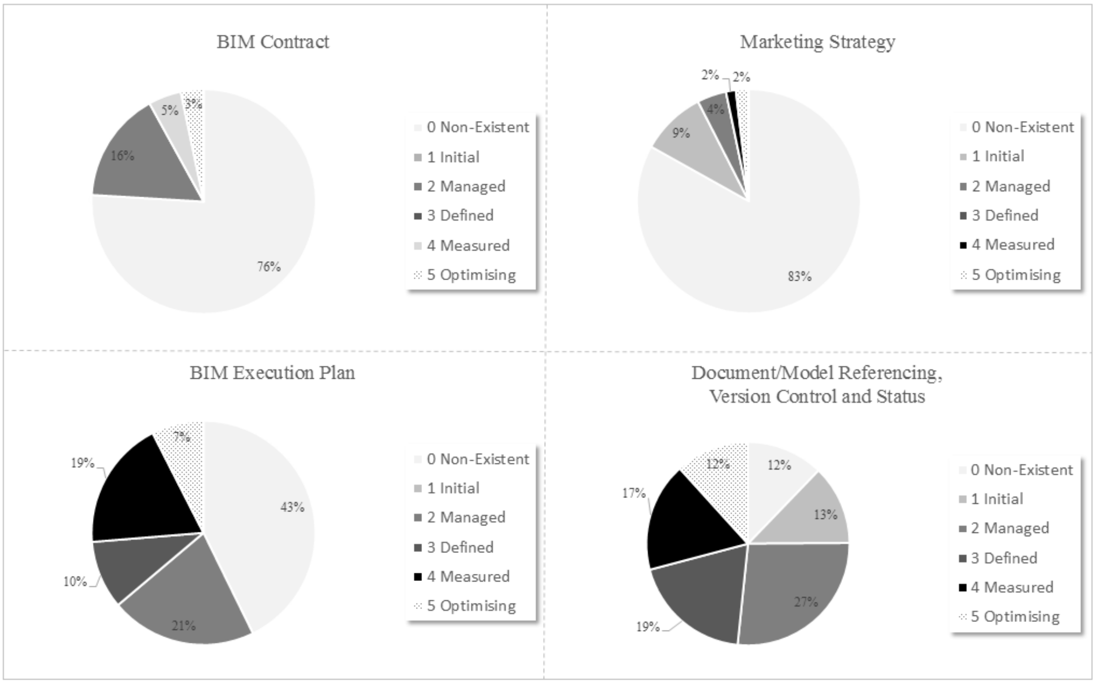

Figure 2 Examples of the distribution of the 213 projects across the six levels of maturity in four different measures

The relationship between the BIM Champion and the rest of the measures

With the development of BIM, new roles have emerged in the AEC industry. ‘BIM Champion’ is one of these emerging roles which is evaluated in the BIM-MM. The BIM Champion is the person who has the motivation and technical skills to guide teams to improve their processes, push BIM utilisation and manage resistance to change (CIC, 2013). The degree of a champion’s engagement varies across different companies and sometimes within the same company across different projects. According to BIM-MM, five levels of maturity of ‘BIM Champion’ are identified (most of other measures have six maturity levels). Analysis of the 213 projects shows that approximately 70% of these projects have a BIM Champion, but with different levels of engagement, this is presented in Table 2.

Table 2 The five maturity levels of 'BIM Champion' and the numbers of projects allocated to each level

Maturity level	Description	No of projects	%
0 Non-Existent	No BIM Champion on this project	66	31 %
1 Initial	BIM Champion is identified but limited time commitment to BIM initiative	63	30 %
2 Managed	BIM Champion with adequate time commitment on this project	56	26 %
4 Measured	Leadership Level BIM Champion with limited time commitment on this project	12	6 %
5 Optimising	Leadership level BIM Champion working closely with BIM Taskforce champion	14	7 %

The overall scores of projects allocated to each level of maturity have been averaged to isolate the effect of having a BIM Champion. For example, there are 66 projects allocated to level 0 Non-Existent BIM Champion. The average 'Project IM Score' of these 66 projects is 14.6% and the average 'Primary Score' is 23.5%. The same approach is applied to projects with all five levels of maturity and the results are shown in Figure 3. Interestingly, the average scores of projects are higher when the BIM Champion has a greater level of involvement in the BIM implementation process. The average of IM Score of projects with Champion level 5 (57.6%) is over three times the average scores with no BIM Champion (14.6%).

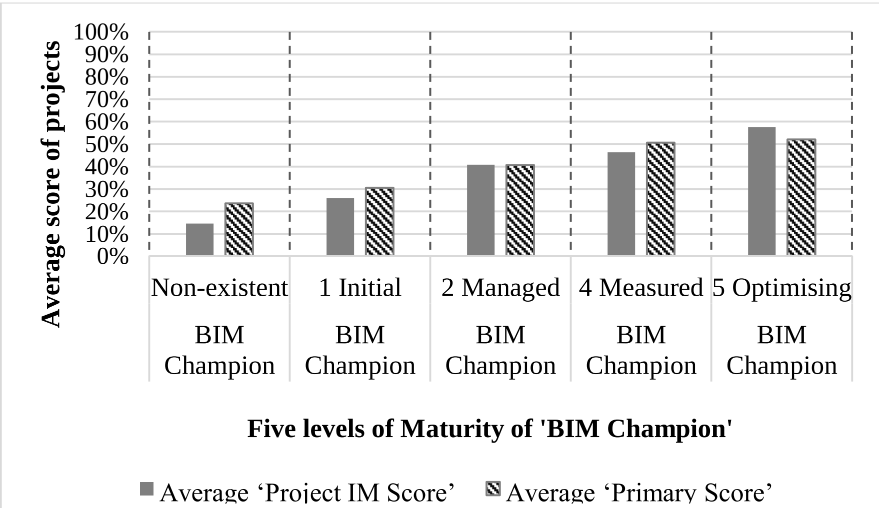

Figure 3 The link between the existence of BIM Champion and the project scores

Another interesting finding is the relationship between BIM Champion and the rest of the individual measures. Figure 4 shows the average scores of each of the ten measures across the 213 projects, split in terms of the BIM Champion level. Overall, there is a significant growth in the average scores of all measures between level 0 and level 4 of BIM Champion. All average scores of level 4 are at least twice the average score of level 0, and in some instances scores are significantly higher. This is exemplified in the BIM Execution Plan (BEP) measure, where average score in level 4 is 10 times the average score of level 0 (3.45 and 0.3 points respectively). The observed relationship between the BIM Champion and the overall scores of projects might be explained in the following manner. BIM Champions undertake actions at the leading edge of BIM's three core dimensions: technology, process and policy (Change Agents AEC, 2013). By looking at these three dimensions, BIM Champions ensure that teams are not treating BIM according to its fractional elements, but rather they are looking at the wider picture. They also define the current status of BIM and guide teams towards desired goals and aims. However, what is unexpected is that half of the measures have lower scores in level 5 compared to level 4. This is exemplified in BEP, Virtual Design Reviews (VDR), BIM Design Data Review, BIM Contract and Marketing Strategy. For instance, there are 1.3 points differences between level 4 and 5 of the VDR. The reason for this is not clear. In the literature there are no detailed studies that focus on the role of BIM Champion and this will require more specific research to identify the underlying cause.

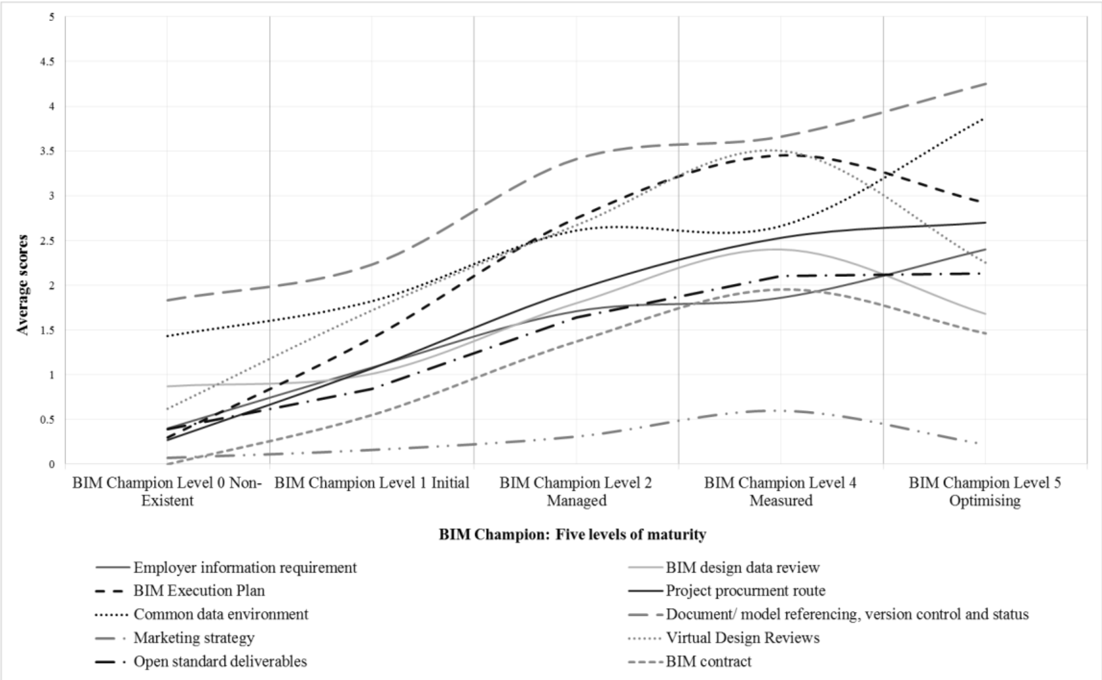

Figure 4 The impact of the BIM Champion on the rest of the measures

DISCUSSION

This comprehensive study generates new insights over previous studies that evaluate BIM in use; in particular, by treating the BIM-MM as a method to observe how BIM is being implemented in the AEC industry. Through the use of BIM-MM, Arup is "aiming to drive a more open conversation about the use of BIM to improve its positive impact across the project spectrum" (Arup, 2014). By doing so, the BIM-MM can be used to engage different project teams in greater dialogue, which informs the decision-making process. This particular role of AMs has not been documented previously in the BIM literature, but it has been acknowledged in different research fields (Cole, 2006).

The maturity levels of the measures vary significantly across the 213 projects and it is important to note that not every project is expected to obtain level 4 Measured or level 5 Optimising. This is similar to the findings of Kam (2015) who argue that it is not necessary to push every project team to achieve the highest levels of maturity in every measure. Instead, the target should be defined by the organisation which should reflect the desired expectations. In their study which applies the VDC Scorecard to 108 projects, (Kam et al., 2013), none of the examined projects have been allocated to 'Innovative Practice' overall (the VDC's Scorecard levels of maturity are Conventional Practice, Typical Practice, Advanced Practice, Best Practice and Innovative Practice).

One interesting finding is the relationship between the BIM Champion engagement in the BIM implementation process and the overall scores of projects. It has been observed that the average score of BIM maturity levels is significantly higher when a BIM Champion has a greater participation in the project. However, part of the project score is directly due to the increase in BIM Champion maturity, but this in no way accounts for all the increase in score. Companies should, therefore strengthen the role of BIM Champions in their practices in order to achieve sharper and more efficient business process of BIM. So no matter what level of maturity the 'BIM Champion' is, their existence, even if with limited time, leads to at least a 10% increase in average scores of projects. However, the case for investing resources in implementing a level '5 Optimising' BIM Champion is perhaps less clear.

CONCLUSIONS

Since 2007, there has been remarkable developments in the field of BIM-AMs, with at least sixteen assessments to date. Despite this growth, there are still fundamental challenges to be addressed. In particular, the shortage of case study projects, which is one of the main challenges in performance measurement. Previous research in the field of BIM-AMs tend to focus on introducing new models without, in many cases, implementing them in practice. This lack of implementation makes it difficult for both academia and industry to understand the practicality of these AMs, their advantages and shortcomings. Arup is pushing the boundaries of BIM and they are currently leading the way in regard to BIM evaluation systems in the UK's AEC industry and beyond. Future directions of the BIM-MM will focus on supplementing the model with financial measures. The BIM Maturity Measure is about to become a key performance standard for Arup's global offices. The authors believe that such implementation is necessary if the opportunities promised by the effective BIM implementation are to be capitalised upon.

REFERENCES

Arup. (2014). The BIM Matuity Measure model. 26.02.2016, from http://www.arup.com/Services/Building_Modelling.aspx

Berlo, L., Dijkmans, T., Hendriks, H., Spekkink, D., & Pel, W. (2012). BIM quickscan: benchmark of BIM performance in the Netherlands. CIB W78.

BRE. (2015). BIM Level 2 Business Systems Certification. Retrieved 26.02.2016, from http://www.bre.co.uk/

Change Agents AEC. (2013). BIM Excellence Performance Measurement Coporate Services

CIC. (2013). BIM Planning Guide for Facility Owners. Version 2.0. Retrieved from: http://bim.psu.edu/

Cole, R. J. (2006). Shared markets: coexisting building environmental assessment methods. *Building Research & Information, 34*(4), 357-371.

Collier, D. (1993). The comparative method. *Political Science: The State of Discipline II, Ada W. Finifter, ed., American Political Science Association*.

Gao, J. (2011). *A Characterization Framework to Document and Compare BIM Implementations on Construction Projects.* Stanford University.

Giel, B. K. (2013). *Framework for Evaluating the BIM Competencies of Building Owners*. [Gainesville, Fla: University of Florida.

Indiana University Architect's Office. (2009). IU BIM Standards. 2015, from http://www.iu.edu/~vpcpf/consultant-contractor/standards/bim-standards.shtml

Kam, C. (2015). Managing BIM Projects, Organizations, and Policies: Turning Aspirations into Quantitative Measures of Success. *Building Information Modeling: BIM in Current and Future Practice*, 267-280.

Kam, C., Senaratna, D., Xiao, Y., & McKinney, B. (2013). The VDC Scorecard: Evaluation of AEC Projects and Industry Trends. Stanford University.

Lee, G., & Won, J. (2014). *Goal-driven method for sustainable evaluation of BIM project*. Paper presented at the European Conference on Product and Process Modelling (ECPPM), VIenna, Austria

McCuen, T. L., Suermann, P. C., & Krogulecki, M. J. (2012). Evaluating Award-Winning BIM Projects Using the National Building Information Model Standard Capability Maturity Model. *Journal of Management in Engineering, 28*(2), 224-230. doi: 10.1061/(ASCE)ME.1943-5479.0000062

Neely, A., Mills, J., Platts, K., Richards, H., Gregory, M., Bourne, M., & Kennerley, M. (2000). Performance measurement system design: developing and testing a process-based approach. *International journal of operations & production management*, *20*(10), 1119-1145.
NIBS. (2007). National Building Information Modeling Standard: Version 1.0- Part 1: Overview, Principles, and Methodologies.
Ragin, C. C. (1989). *The comparative method moving beyond qualitative and quantitative strategies*. Berkeley, CA: Berkeley, CA : University of California Press.
Schweber, L., & Haroglu, H. (2014). Comparing the fit between BREEAM assessment and design processes. *Building Research & Information*, *42*(3).
Succar, B. (2010). Building information modelling maturity matrix. *Handbook of research on building information modelling and construction informatics: Concepts and technologies, J. Underwood and U. Isikdag, eds., IGI Publishing*, 65-103.
Succar, B., Sher, W., & Williams, A. (2012). Measuring BIM performance: Five metrics. *Architectural Engineering and Design Management*, *8*(2), 120-142.

Appendix C. Survey questionnaire applied in this thesis

Building Information Modelling Assessment Methods (BIM-AMs)

I am Ammar Azzouz, a PhD candidate at the University of Bath, Department of Architecture and Civil Engineering. My research focuses on Building Information Modelling Assessment Methods (BIM-AMs). AMs are methodologies and theoretical models that evaluate BIM level of maturity in a project, an organisation, a team or an individual. In my initial research I gathered 13 BIM-AMs developed in the academic and industrial levels.

I hope you could generously spend 5-10 minutes to complete this questionnaire. Your response to this evlauation questionnaire may be published anonymously.

Profession:	Name (optional):	Email (optional):
Job title:	BIM Experience? Yes No	Years of BIM experience (if any):

1. What is Building Information Modelling?

How would you define BIM?

2. What are the top five benefits and challenges of BIM? Please rank in order:

Top five benefits	Top five challenges
1.	1.
2.	2.
3.	3.
4.	4.
5.	5.

3. Did you know what AMs were before?

Yes		No
If yes, which one(s):		

4. Do you think there is a need evaluate the level of maturity of BIM?

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
In your opinion, what is the importance of measuring and assessing the implementation of BIM?				
1. 2. 3. 4.				

5. Table below shows, in no order, the top indicators measured in the current BIM-AMs. In your experience rank these indicators from 1-8 according to their importance (1 is the most important, 8 is the least important).

A shortlist of BIM Indicators	**Rank from 1-8**
Data Richness/ Level of Detail	
Goals/ Objectives/ Visions/ Leadership	
Technology/ Tools/ Applications/ Software	
Use of Modelling/ Model Use Life Cycle	
Roles/ Disciplines/ Responsibilities/ HR/ Personnel	
Stakeholder Involvement	
Delivery Method/ Network/ Sharing Method	
Standard	
Other comments:	

What other comments do you have on the AM you completed? Could you describe advantages and challenges?

If you would like to stay in contact my email address is: aa2038@bath.ac.uk

Ammar Azzouz

Thank you very much!