Building Information Modelling: conceptual constructs and performance improvement tools

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Declaration

This *thesis by published works* is submitted for the award of Doctor of Philosophy from the University of Newcastle.

Some of the papers included as part of this submission are jointly authored and I hereby certify that I have included a written statement from each co-author or project leader - endorsed by the Faculty Assistant Dean (Research Training) - attesting to my contribution to the joint publications. Where work embodied in this thesis has been conducted in collaboration with other researchers, or in other institutions, I have included a statement clearly outlining the extent of collaboration, with whom and under what auspices.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

I give consent to the final version of my thesis being made available worldwide when deposited in the University's Digital Repository, subject to the provisions of the Copyright Act 1968.

Bilal Succar

December 16, 2013

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Thesis Overview

Building Information Modelling (BIM) is a set of technologies, processes and policies enabling multiple stakeholders to collaboratively design, construct and operate a facility.

There are numerous challenges attributed to BIM adoption by industry and academia. These represent a number of knowledge gaps each warranting a focused investigation by domain researchers. This study does not isolate a single gap to address but espouses a holistic view of the knowledge problem at hand. It contributes to the discussion a set of conceptual constructs that clarify the knowledge structures underlying the BIM domain. It also introduces a number of practicable knowledge tools to facilitate BIM learning, assessment and performance improvement.

This study is delivered through complementary papers and appendices to answer two primary research questions. The first explores the knowledge structures underlying the BIM domain whilst the second probes how these knowledge structures can be used to facilitate the measurement and improvement of BIM performance across the construction industry.

To address the first question, the study identifies conceptual clusters underlying the BIM domain, develops descriptive taxonomies of these clusters, exposes some of their conceptual relationships, and then delivers a representative BIM framework. The BIM framework is composed of three-axes which represent the main knowledge structures underlying the BIM domain and support the development of functional conceptual models.

To address the second question, BIM framework structures are extended through additional concepts and tools to facilitate BIM performance assessment and development of individuals, organizations and teams. These additional concepts include competency sets, assessment workflows and measurement tools which can be used to assess and improve the BIM performance of industry stakeholders.

In addressing these research questions, a pragmatic approach to research design based on available literature and applicable theories has been adopted. By combining several research strategies, paradigms and methods, this study (1) generates several new conceptual structures (e.g. frameworks, models and taxonomies) which collectively clarify the knowledge structures underlying the BIM domain; and (2) develops a set of workflows and tools that facilitate BIM assessment, learning and performance improvement.

This study delivers an extendable knowledge structure upon which to build a host of BIM performance improvement initiatives and tools. As a set of complementary papers and appendices, the study presents a rich, unified yet multi-layered environment of conceptual constructs and practicable tools; supported by a common framework, a domain ontology and simplified visual representations. Individually, each paper introduces a new framework part or solidifies a previous one. Collectively, the papers form a cohesive knowledge engine that generates assessment systems, learning modules and performance improvement tools.

Thesis structure

The thesis is delivered in three parts - introduction document, published papers and supporting appendices:

Part I: introduction document

The introduction document identifies the research questions, research design and study deliverables. Part I includes eleven sections:

Sections 1-3 introduce the research context, research background and discuss the importance of BIM;

Sections 4-6 identify the research questions underpinning this study, discuss the conceptual background and overall research design;

Sections 7-8 introduce a hierarchy of conceptual structures and clarify how the BIM framework has been constructed;

Section 9 introduces the study's research deliverables, the common themes underlying the submitted papers, and how different research deliverables aggregate into a conceptual and practical continuum;

Section 10 provides a conclusion, identifies a study limitation and introduces its future extensions; and

Section 11 includes the introduction document's bibliographic references.

Part II: published papers

Part 2 includes nine papers – in three types - submitted as part of this thesis. Paper types are explained in section 9 of Part I:

Paper A1: A Proposed Framework to Investigate Building Information Modelling through Knowledge Elicitation and Visual Models

Paper A2: The BIM Framework: a Research and Delivery Foundation

Paper A3: Building Information Modelling Maturity Matrix

Paper A4: The Five Components of BIM Performance Measurement

Paper A5: Measuring BIM Performance: Five Metrics

Paper A6: An integrated approach to BIM competency assessment, acquisition and application

Paper B1: Building Information Modeling: analyzing noteworthy publications of eight countries using a knowledge content taxonomy

Paper B2: A proposed approach to comparing the BIM maturity of countries

Paper C: BIM in Practice - BIM Education, a Position Paper by the Australian Institute of Architects and Consult Australia

Part III: appendices

Part III includes six appendices to clarify and support submitted papers:

Appendix A: the BIM ontology

Appendix B: BIM knowledge content taxonomy

Appendix C: citations of published papers

Appendix D: focus groups info sheet and feedback form

Appendix E: statements of contribution

Appendix F: aggregation of all bibliographic references cited in this study

PART I
INTRODUCTION DOCUMENT

This document introduces the research topics, questions, design and deliverables. It summarizes the contribution each submitted paper made towards this study, explores common research themes across papers, and provides an insight into future study extensions.

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1 Research context

Building Information Modelling (BIM) is the *current expression* of technical and procedural innovation within the construction industry. It is a methodology that generates, exchanges and manages a constructed facility's data throughout its life cycle. While BIM is solidly rooted in technological advances, partially transferred from other industries, it extends into the realm of social exchanges between organizational actors. A focused analysis of the BIM domain is thus necessarily an in-depth investigation of multi-layered organizational dynamics, changing knowledge structures across industry sectors and evolving market requirements. To understand BIM, its disparate parts must be identified as well as the sum of these parts; individual deliverables must be defined alongside the requirements for these deliverables; and individual concepts and tools must be recognized in addition to the relationship between them. In essence, to holistically understand BIM, it must be considered as a multi-faceted paradigm, an emergent interdisciplinary field of research and application within the construction industry.

2 Research background

BIM concepts, tools and workflows have been extensively discussed in peer-reviewed literature, industry seminars and online public discussions. Within these, BIM is described as a catalyst for change (Bernstein, 2005) poised to reduce industry's fragmentation (CWIC, 2004), improve its efficiency/effectiveness (Hampson & Brandon, 2004) and lower the high costs of inadequate interoperability (NIST, 2004). These assertions – abridged as they may be - include several mental constructs derived from organizational studies, information systems and regulatory fields. Such divergence and breadth highlight the need for clear conceptual constructs – taxonomies, ontologies, models and frameworks - to organize domain knowledge, facilitate BIM learning within industry and academia, and enable the development of practicable performance improvement tools. Several conceptual constructs are developed as part of this study and will be explored in subsequent sections.

3 Importance of BIM

The importance of BIM stems from its significant benefits *and* substantial challenges. As summarized in sections 3.1 and 3.2, BIM concepts and workflows promise to deliver substantial benefits to "all participants in the process of designing, constructing, owning and refurbishing buildings" (BIS, 2011, p. 7). These deliverables however are subject to substantial cultural challenges, legal barriers and process complexity. Some of the more impactful benefits and challenges are discussed below:

3.1 BIM benefits

The benefits attributed to BIM represent unique project deliverables and invariably reflect industry's long-term expectations from this *new CAD paradigm* (Ibrahim, Krawczyk, & Schipporeit, 2004, p. 1). Below is a non-exhaustive list summarizing BIM benefits:

- BIM will reduce industry's fragmentation (CWIC, 2004);
- BIM significantly reduces labour costs, production rework and installation conflicts (Khanzode, Fischer, & Reed, 2008);
- BIM creates a transparent project environment (Leicht & Messner, 2008);
- BIM enhances collaboration between construction professionals (Alshawi & Faraj, 2002);
- BIM is an "integration of product and process modelling" (Kimmance, 2002, p. 6);
- BIM allows rapid/accurate updating of changes; reduction of effort required for establishing spatial programmes; improved communication within the project team; and elevated confidence in scope completeness (Manning & Messner, 2008) as reported in (Linderoth, 2010);
- BIM results in a "clear improvement in engineering design quality, in terms of error-free drawings, and steadily increasing improvement in labour productivity" (Kaner, Sacks, Kassian, & Quitt, 2008, p. 303);
- A combined BIM/Lean approach is more efficient than a Design-Bid-Build or a Design-Build project delivery process (USAF, 2010);

- BIM can address the emerging challenges of sustainability within the construction industry (Watson, 2010);
- The adoption of BIM principles will allow all construction industry players to gain "substantial benefits in financial terms" (BIS, 2011, p. 7); and
- BIM has many benefits including: automated assembly, better design, controlled whole-life costs and environmental data, enhanced processes, higher production quality, and improved customer service (ACG, 2010).

3.2 BIM challenges

Industry's expectations of BIM are neither readily nor necessarily matched by reality. Numerous studies have shown that implementing BIM presents significant challenges in BIM education, multidisciplinary workflows and organizational transformation. A non-exhaustive list summarizing these is provided below:

- BIM adoption and collaboration is negatively affected by construction industry's confrontational culture (Watson, 2011);
- BIM is adversely influenced by "organizational and cultural divisions between designers and builders and between contractors and subcontractors" (Dossick & Neff, 2009, p. 466);
- BIM implementation across an organization has significantly different, and even competing requirements, to BIM implementation on projects (Kunz, 2012);
- There are only a few "procedures or tools to guide practical BIM implementation processes" (Mäkeläinen, Hyvärinen, & Peura, 2012, p. 497);
- BIM adoption is affected by the lack of interoperability between different software platforms (Eastman, Teicholz, Sacks, & Liston, 2011);
- There are many business and legal barriers to collaborative BIM processes (Sebastian, 2010);
- BIM causes workflow disruptions and requires a reconsideration of construction business practices (Mihindu & Arayici, 2008);
- BIM implementation has resulted in the emergence of new knowledge and skill gaps within industry (Mihindu & Arayici, 2008); and

- BIM technologies and processes represent a disruptive paradigm shift affecting established processes within the construction industry (Shelden, 2009) (Younas, 2010) (Watson, 2011) and “one of the most disruptive (positive or negative) episodes in the history of architectural education” (Denzer & Hedges, 2008, p. 9).

In addition to these domain-specific challenges, BIM reflects the complex and interdependent nature of design and construction projects (Austin, Newton, Steele, & Waskett, 2002) (Froese, 2010) and its adoption by industry is challenged by the same factors affecting technology-adoption in general. In their research covering the construction industry, Peansupap and Walker (2005), identified several factors underlying the slow uptake of information and communication technology (ICT) by organizations. These factors include: the complex nature of the construction industry; ICT immaturity levels; poor availability of tools for evaluating the benefits of using ICT; and lack of understanding of ICT implementation processes. These factors are likely to apply as well to BIM - as a technology-driven process within the construction industry - and need to be addressed if BIM is to be adopted and its benefits realized.

4 Research questions

Industry's far-ranging expectations from BIM tools and workflows and the challenges of meeting these expectations (section 3.2) uncover numerous knowledge gaps, each of which warrants investigation. Rather than investigating each gap individually, this study espouses a holistic view and adopts two complementary research questions:

Research question 1: What are the knowledge structures underlying the BIM domain?

> This is a *hypothetical question* (Dillon, 1984) intended to generate a theoretical framework through conceptual analysis. This question is addressed through the development of a theoretical framework that organizes BIM concepts and their relationships.

Research question 2: How can these knowledge structures be harnessed to assist industry stakeholders to adopt BIM or improve their BIM performance?

> This question is *demonstrative* (Dillon, 1984); intended to illustrate the usefulness of the framework through representative models and applicable tools. This question is addressed through generating a set of practicable tools that can be used by industry and academia to measure BIM competency, inform BIM implementation and facilitate BIM education.

This study addresses these research questions through the iterative development of conceptual constructs and practicable tools (sections 8 and 8.6) which were consecutively delivered through interdependent publications (Part II). Before summarizing the collective deliverables of this study (section 10), the next sections clarify the research aims and explore the conceptual background informing this investigation and guiding its research approach.

5 Research aims and objectives

The main research aim of this study is to generate conceptual constructs and practicable tools to facilitate *structured BIM adoption* by industry and academia. This is *practically important* because BIM implementation - as an advanced technology-driven process – needs to be well-structured and well-managed as a condition of its success (Peansupap & Walker, 2005) (Green & Hevner, 2000).

This research aim translates into a number of complementary research objectives and sub-objectives; some were identified at the start of the study, others were progressively added or refined. Research objectives can be summarised as follows:

- Reduce domain complexity
- Delimit BIM concepts and identify their relationships
- Develop a visual language to capture and represent knowledge
- Develop numerous interconnected conceptual constructs that can be:
    - Adopted or extended by fellow researchers and practitioners
    - Transformed into performance assessment and improvement tools
    - Applied across disciplines, technologies and markets
- Deliver research outcomes that retain relevance and representation irrespective of advances in BIM-related technologies
- Lay the foundations for the future development of a *technology adoption meta-framework* and a *knowledge-representation mid-level theory*
- Exchange domain knowledge with industry stakeholders
- Encourage future PhD students to follow the *thesis by publication* route

6 Conceptual background

The research questions, aims and objectives discussed in sections 4 and 0 are a reflection of a set of paradigms, theories and concepts collectively forming the study's conceptual background. This conceptual background - according to Maxwell (2005) - is in turn based on several sources including: previous research; applicable theories; the researcher's own experiential knowledge; and the researcher's thought experiments. These are discussed below:

6.1 Previous research

This study includes two main literature reviews and several complementary ones distributed across included papers (section 10.1). The first main literature review was conducted in paper A2 (all papers are included in Part II) to inform the development of a conceptual framework representing the BIM domain. At the time paper A2 was published (late 2008), no substantial BIM frameworks existed[1] and none of the reviewed *noteworthy BIM publications* (NBPs – e.g. BIM guides, protocols or specifications) were based on an explicit conceptual structure which could be readily adopted or improved. The absence of conceptual structures within NBPs constituted a significant research gap, which was targeted and partially addressed by paper A2. A follow-up, more extensive literature review conducted six years later (paper B1, 2013) identified several new BIM frameworks - including those of Taylor and Bernstein (2009), Jung and Joo (2010), Singh, Gu, and Wang (2011), Feng, Mustaklem, and Chen (2011) and Cerovsek (2012) - thus signalling a narrowing of this once wide knowledge gap.

The second main literature review was conducted in paper A3 and was later partially updated in paper A5. The review covered numerous maturity, business performance, excellence and quality management models to identify a suitable assessment structure for measuring and improving BIM performance. However, these models were found to

[1] A partial, theoretical BIM framework was available through TNO's BIM wiki (http://wiki.e-bouw.org/index.php?title=BIM - Building Information Model(ing)), last accessed September 2008. The actual website is no longer available but its textual contents can be gleaned from a web archive snapshot (http://bit.ly/12a93wN) and this file: http://www.tno.nl/downloads/The%20BIM%20Landscape.pdf, last accessed June 28, 2013.

lack the flexibility required for assessing different organizational scales (e.g. individuals, organizations, teams and markets - see Table 3 in A3) and did not differentiate between the notions of capability (an ability to perform a task) and that of maturity (degrees of excellence in performing a task). The lack of a model suitable for assessing BIM performance across different organizational scales presented a second significant knowledge gap which was targeted and addressed in published papers: paper A3 introduced several conceptual constructs and tools that can be applied to assess organizations, teams and *larger organizational scales* (e.g. country-wide maturity); and paper A6 introduced conceptual concepts and tools that can be applied to assess the BIM competency of individuals and groups.

These two main literature reviews were complemented by additional reviews spread across other papers including: benefits of conceptual mapping and knowledge visualization (paper A1), and an analysis of the different connotations of the term 'competency' as applied to professional abilities (paper A6). These main and complementary reviews helped identify the two research questions; guided the development of new methods to assess BIM performance; and identified a visual approach to simplify and represent BIM concepts and their relationships.

6.2 Applicable theories

Several existing theories informed the initial analysis of BIM concepts and their relationships. These theories offered clear insights into how to understand complex knowledge structures and their component parts. However, when attempting to apply these established theories to clarify the knowledge structures underlying the BIM domain *and* to develop practicable tools based on these constructs, the limitations of each theory became evident.

Table 1 identifies five theories initially considered – and then discounted - as applicable to guide this study and help answer the two research questions:

Table 1. Existing theories employed to facilitate BIM understanding

THEORY	HOW THE THEORY INFORMED THIS STUDY
Systems Theory as applied to Organizations and Management	Systems Theory provides a framework by which groups of elements and their properties may be studied jointly to understand outcomes (Ackoff, 1971) (Chun, Sohn, Arling, & Granados, 2008). **Study considerations and theory limitations:** using Systems Theory, BIM can be analysed as either an *abstract system* or as a *system of systems*; the first deals with concepts without attending to their practical application while the second treats BIM as a collection of interrelated abstract *and* concrete systems. While BIM can be considered in many respects as a System of Systems (Cerovsek, 2012), such an approach does not allow the analysis of BIM concepts and relationships from a non-systems' perspective. Also, Systems Theory is applicable in understanding machine-machine and human-machine interactions, but it is not applicable in understanding human-human interactions.
Systems Thinking as applied to Knowledge Management	Systems Thinking focuses on causes, rather than events, but does not isolate the smaller parts of the system being studied. Rather, it considers the numerous interactions of the system in question (Chun et al., 2008). **Study considerations and theory limitations:** through Systems Thinking, BIM can be analysed as a *knowledge system* leveraged to achieve organizational and industrial goals. Systems Thinking can identify drivers of successful BIM implementation; however, actual implementation steps cannot be identified. To facilitate BIM implementation, both activities *and* causes/effects need to be understood. Also, granular parts of the knowledge system – and their interactions - are *as important* to analyse as the knowledge system itself.
Diffusion of Innovation (DoI)	DOI theory attempts to "define the process by which an innovation is communicated through certain channels over time among the members of a social system"(Rogers, 1995, p. 5). That is, DOI theory seeks to explain the dynamics of why/how a new technology spreads. **Study considerations and theory limitations:** Through DOI, the diffusion of BIM - as an *innovative technological solution* proliferating across the construction industry - can be analysed (Fox & Hietanen, 2007) (Mutai, 2009). However, DOI does not facilitate the understanding of BIM as an interacting set of technologies, processes and polices; nor does it facilitate the generation of practicable performance improvement tools.
Technology Acceptance Model (TAM)	TAM theorizes that an individual's acceptance of a new technological solution is influenced by its perceived usefulness and ease of use. TAM incorporates several theoretical constructs including subjective norm, voluntariness, image, job relevance, output quality and result demonstrability (Davis, 1989) (Venkatesh & Davis, 2000). **Study considerations and theory limitations:** as a technology-driven solution, BIM adoption by individuals – and by extension project teams - can be analysed under this model. However, this model cannot be applied to organizational systems, or to identify the relationship between project teams.

Complexity Theory	Complex systems are comprised of a large number of components and causal connections amongst them. Each component is self-contained yet shows a high degree of synergy with other components - where the whole is more than the sum of its parts (Homer-Dixon, 2001) (Froese, 2010). **Study considerations and theory limitations:** understanding BIM as *a complex system* allows the identification of its components and their interconnectedness. However, like many other established theories, Complexity Theory does not facilitate the development of practicable performance improvement tools.

In summary, the theories listed[2] in Table 1 can be applied in analysing BIM concepts and their relationships. However, they are difficult to apply in generating practicable tools from that analysis. Rather than adopting an existing theory to address the research questions, the author opted to *develop a new theoretical framework*; an inductive approach "[more suitable for researchers who are more concerned about] the correspondence of their findings to the real world than their coherence with existing theories or laws" (Meredith, Raturi, Amoako-Gyampah, & Kaplan, 1989, p. 307). This decision to develop a new theoretical framework - instead of testing concepts and relationships against existing theories - is in line with Glaser and Strauss' 1967 recommendation where they lamented how social researchers had become overly concerned with testing existing theories while neglecting the process of generating them (Glaser & Strauss, 1967) (Blaikie, 2000). Also, developing a theoretical framework - rather than adopting existing theories – provides this study with the theoretical flexibility it needs to address the two complementary research questions (section 4).

[2] Coordination, Organization and Structuration theories were also reviewed as part of this study but found to be less applicable towards addressing the research questions; they were thus excluded from Table 1.

6.3 Experiential knowledge

This researcher's industry-based BIM expertise[3] has played a significant role in this study. The development of the framework has been informed by a "combination of grasping and transforming experience" (Kolb, Boyatzis, & Mainemelis, 2000, p. 2).

While recognizing the *possibility of bias* (Maxwell, 2005), the researcher acknowledges the *impossibility of detachment* (Blaikie, 2000) from the research topic. He thus adopted the view promoted by Glesne, Peshkin and Strauss (as discussed in Blaikie, 2000) which argued for researchers to *mine their own experience* while engaging in critical subjectivity, a "quality of awareness in which we do not suppress our primary experience; nor do we allow ourselves to be swept away and overwhelmed by it; rather we raise it to consciousness and use it as part of the inquiry process" (Reason, 1988, p. 12) (Reason, 1994).

6.4 Thought experiments

Thought experiments or *speculative model-building exercises* (Lave & March, 1993) are mental representations which allow researchers to suggest plausible explanations that interpret observations, and then, to support or disprove them (Maxwell, 2005). Thought experiments build-upon a researcher's experiential knowledge (section 6.3) to generate "concepts, relations, features, chunks, plans, heuristics, theories [and] mental models" (Cooke & McDonald, 1986, p. 1424).

As it is difficult - and arguably undesirable - to discount the role personal experiences play in informing research (Corbin & Strauss, 2008), this study employs the researcher's experiential, domain-specific knowledge to generate a set of complementary models which explain BIM concepts and their relationships. Through thought experiments, the researcher "[thoroughly immersed himself] in the topic under consideration in order to pull the commonalities and patterns into a unique, insightful perspective". Through such immersion, the researcher was able to see "connections and patterns in what was heretofore just a series of inexplicable events or studies"(Meredith, 1993, p. 8).

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[3] The researcher is an industry BIM advisor and has worked as such since 2004.

7 Research design

This thesis does not seek to prove, disprove or compare phenomena but rather to discover the underlying structures of a nascent domain of knowledge. To satisfy the research questions identified in section 4, this study adopted an *interpretive paradigm,* a *retroductive strategy,* and an exploratory *mixed-data* collection methodology. These are briefly discussed below:

7.1 Research paradigms

Research paradigms are the *philosophical perspectives* (or world views) about what constitutes *valid research* (Myers, 1997a). Research paradigms are based on *epistemological[4], ontological[5] or metaphysical[6] assumptions* covering the nature of knowledge and how it can be obtained (Myers, 1997b) (Meredith et al., 1989). This study has adopted a paradigm closer to interpretive and critical assumptions than to positivist ones. As will be evident in the published papers, the research conducted does not strive to confirm an existing phenomenon or to measure it against another but seeks to bring meaning and structure to a series of phenomena (BIM concepts and their relationships) through a human perspective. The study also includes epistemological elements pertaining to critical thought – not only to study BIM as a set of interrelated phenomena within a historical context but also to inform how BIM is implemented within organizations and the wider industry. Below is a summary of the three research paradigms followed by (section 7.1.4) how this thesis is positioned relative to them:

[4] Epistemological assumptions relate to the notions of *knowledge* and how it can be achieved.
[5] Ontological assumptions or beliefs have to do with the "*essence of phenomena* under investigation; that is, whether the empirical world is assumed to be objective and hence independent of humans, or subjective and hence having existence only through the action of humans in creating and recreating it"(Orlikowski & Baroudi, 1991, p. 7).
[6] Metaphysical assumptions relate to the notions of *truth* and its origin.

7.1.1 Positivist paradigm

The *positivist paradigm* has its roots in the natural sciences and is premised on the existence of *a priori*, real, unidirectional and fixed cause-effect relationship that is “capable of being identified and tested via hypothetic-deductive logic and analysis” (Orlikowski & Baroudi, 1991, p. 9). Positivists generally assume that reality is *objectively given* and can be measured independently of the observer and his/her instruments. Positivist generally attempt to test theory and increase the predictability of a measurable phenomenon (Myers, 1997a).

7.1.2 Interpretive paradigm

The *interpretive paradigm* assumes that people create and associate their own subjective meanings as they interact with the world around them. Interpretive research “does not predefine dependent and independent variables, but focuses on the full complexity of human sense making as the situation emerges” (Myers, 1997a - Interpretive Research section) as attributed to (Kaplan & Maxwell, 2005). Interpretive thought assumes, according to Orlikowski and Baroudi (1991, p. 15), that researchers “can never assume a value-neutral stance, and [are] always implicated in the phenomena being studied. Researchers' prior assumptions, beliefs, values, and interests always intervene to shape their investigations”.

7.1.3 Critical paradigm

The *critical paradigm* assumes that “social reality is historically constituted, and hence that human beings, organizations, and societies are not confined to [current or existing situations]” (Orlikowski & Baroudi, 1991, p. 19). Critical thought aims to investigate and expose – what is assumed to be – contradictions and restrictions within social systems (including groups, organizations and societies) and thus transform these social systems (Myers, 1997a). A single phenomenon, according to critical thought, cannot be isolated from its social environment but must be studied within its socio-historical context.

7.1.4 Discussion: adopting a mixed paradigm

At the heart of this study is the researcher’s contention that knowledge does not reside at opposite extremes of deductivist and inductivist thought. While objective reality – independent from researchers – does exist and has intrinsic value, measuring it without the results being altered by a researcher’s preconceptions, research approach or measurement tools cannot be demonstrated. Irrespective of the above, choosing a single epistemological position is neither helpful nor necessary. As discussed in Walsham (1995, p. 382), Lee (1991) states that research paradigms are *complementary*, and positivist and interpretive approaches can be combined. This study thus adopts a mixed paradigm and complements it with a mixed research strategy as discussed below:

7.2 Research strategy

A research strategy is the approach adopted to answer research questions. As identified by Blaikie (2000), there are four main research strategies: inductive, deductive, abductive and retroductive. As will be discussed in section 7.2.4, retroduction is the research strategy best suited to underpin this study. However, retroduction on its own is not enough to address both research questions (section 4). According to Atkinson (2011), retroduction - or 'hypothesis formulation' – is but the first stage of an enquiry. The hypothesis must then be tested using *both* induction and deduction. Through *inductive creativity* (Reisman, 2004) (Saaty, 1998), new frameworks, new taxonomies or new theoretical predictions can be generated. However, since an inductive strategy can only *make a prediction* or s*uggest a solution* (by amalgamating previous solutions or by proposing a new one) but cannot *test* that solution or *confirm* that prediction, a deductive strategy is then needed to *test* the theory and *confirm* its validity. Below is a summary of the four research strategies:

7.2.1 Deduction

Deductive reasoning provides theoretical explanations on the world and then, by a process of trial and error, uses data to reject false ones. Theories "which survive this critical process are provisionally accepted, but never proven to be true" (Blaikie, 2000, p. 105). Deduction attempts to confirm or dispute a theoretical prediction and does not generate a prediction on its own. Deduction can only strengthen, weaken or disprove *a priori* theoretical propositions or predictions. In essence, conceptual deductions occur when a framework or a theory – regardless how it was formed - is compared with reality.

Since this thesis is concerned with uncovering and representing the knowledge structures underlying the BIM domain, a deductivist approach is not suitable as a primary research strategy. However, as discussed in section 7.2.4, a deductive approach to test inductively generated models is partially required.

7.2.2 Induction

Conceptual induction is an approach where researchers analyse recurring phenomena to infer the underlying structure of a system. The system under investigation does not necessarily need to be complex but can be a "human interpretation or conceptualization for which explicit rules have never been explicated" (Meredith, 1993, p. 9). With conceptual induction, the objective is to use a system's elements to describe a specific phenomenon accurately and explain how it occurs. The accuracy of the description and explanation is "usually based on the consistency between the explanation *inferred* and the description of the phenomenon, particularly its elements and [their] relationships" (Meredith, 1993, p. 9). According to Popper (2002, p. 27), an explanation or inference is considered 'inductive' when "it passes from *singular statements* (sometimes called 'particular' statements), such as accounts of the results of observations or experiments, to *universal statements*, such as hypothesis or theories".

Since the candidate did not start with a blank slate as required by inductivists (Glaser & Strauss, 1967), a purely inductive strategy will not be suitable. This is especially true as the candidate developed this study in the "context of ontological, conceptual and theoretical assumptions" held by the researcher/practitioner (Blaikie, 2000; White, 1997, p. 745).

7.2.3 Abduction

The *abductive* research approach was proposed by the philosopher Charles Sanders Pierce (Miller & Brewer, 2003) in the early 1930s and is mostly – if not exclusively - applicable to social sciences (Blaikie, 2000). Abductive research refers to the "process used to generate social scientific accounts from social actors' accounts; for deriving technical concepts and theories from lay concepts and interpretations of social life" (Blaikie, 2000, p. 114). That is, abduction gives "access to any social world [by] the accounts given by the people who inhabit it. These accounts contain the concepts that people use to structure their world - the meanings and interpretations, the motives and intentions which people use in their everyday lives and which direct their behaviour" (Atkinson, 2011, p. 3).

Since this study does not seek to represent reality through the experiences of social actors other than the candidate's own (refer to section 6.3), the abductive research approach has not be used in this research.

7.2.4 Retroduction

According to Blaikie (2000, p. 108), the *retroductive strategy* is the "logic of enquiry associated with the philosophical approach of Scientific Realism". Similar to deductive research, it "starts with an observed regularity but seeks a different type of explanation". Using retroduction, events are explained *by postulating and identifying structures and causal powers capable of generating them* (Sayer, 1992); and by locating the "real underlying structure or mechanism that is responsible for producing the observed regularity" (Blaikie, 2000, p. 25). Retroduction uses "creative imagination and analogy to work back from data to an explanation" and involves the "building of hypothetical models as a way of uncovering the real structures and mechanisms which are assumed to produce empirical phenomena" (Blaikie, 2000, p. 25). In constructing these hypothetical models, “ideas may be borrowed from known structures and mechanisms in other fields” (Atkinson, 2011, p. 2). According to (Downward & Mearman, 2007, p. 2), retroduction “can be contrasted to other research strategies, such as deduction or induction, as not simply developing specific claims from general premises nor general claims from specific premises, respectively, but the ‘mode of inference in which events are explained by postulating (and identifying) mechanisms which are capable of producing them’ (Sayer, 1992, p. 107).”

This study organizes the domain knowledge by inferring BIM concepts and their relationships, generating theoretical constructs (frameworks and models) to represent these concepts/relations, and then using these constructs to develop tools for practical application. Such an approach is considered an *artificial reconstruction of reality* (Meredith et al., 1989, p. 307), a hypothesis-building exercise which mostly lends itself to the retroductive research strategy. However, as discussed earlier in this section, a retroductive strategy on its own is not sufficient to address the study’s requirements.

7.2.5 Discussion: adopting a mixed strategy

In summary, this study adopted a mixture of research strategies to formulate the BIM framework and other knowledge constructs which – hypothetically - underlie the BIM domain. In generating this hypothesis, this study has employed an inductivist strategy to infer *general* statements from necessarily *specific* experiential knowledge. Finally, it employed deductivist strategies - through collecting exploratory data (section 7.4) - to test whether these conceptual models can be considered as an accurate representation of objective reality. Such amalgamation of inductive and deductive approaches is not peculiar to this study but - according to Downward and Mearman (2007) - combining them *is central* to retroductive activity.

7.3 Research method

A research method represents how a study moves "from the underlying philosophical assumptions to research design and data collection" (Myers, 1997a). According to Mitroff and Mason (1982), as mentioned in Meredith et al. (1989), research methods can be classified according to two 'dimensions'. The first dimension is referred to as *rational/existential* and is concerned with the researcher's underlying philosophical assumptions (ontological, epistemological or metaphysical). Through this dimension, the nature of knowledge/truth can be defined as *rational* - purely logical and independent from man, or as *existential*; can only be understood through human experience. The second dimension is referred to as *natural/artificial*[7] and is concerned with the source and type of data to be used within research. Through this dimension, the nature of data/information to be collected is either described as *natural* – objective data derived from direct observation, or *artificial*; derived from interpretation and the artificial reconstruction of reality.

Using the aforementioned classification, Meredith et al. (1989) generated a matrix (Figure 1) which positions research methods along the two dimensions underlying research design:

[7] Mitroff and Mason (1982) originally referred to this dimension as the empiricism/idealism dimension

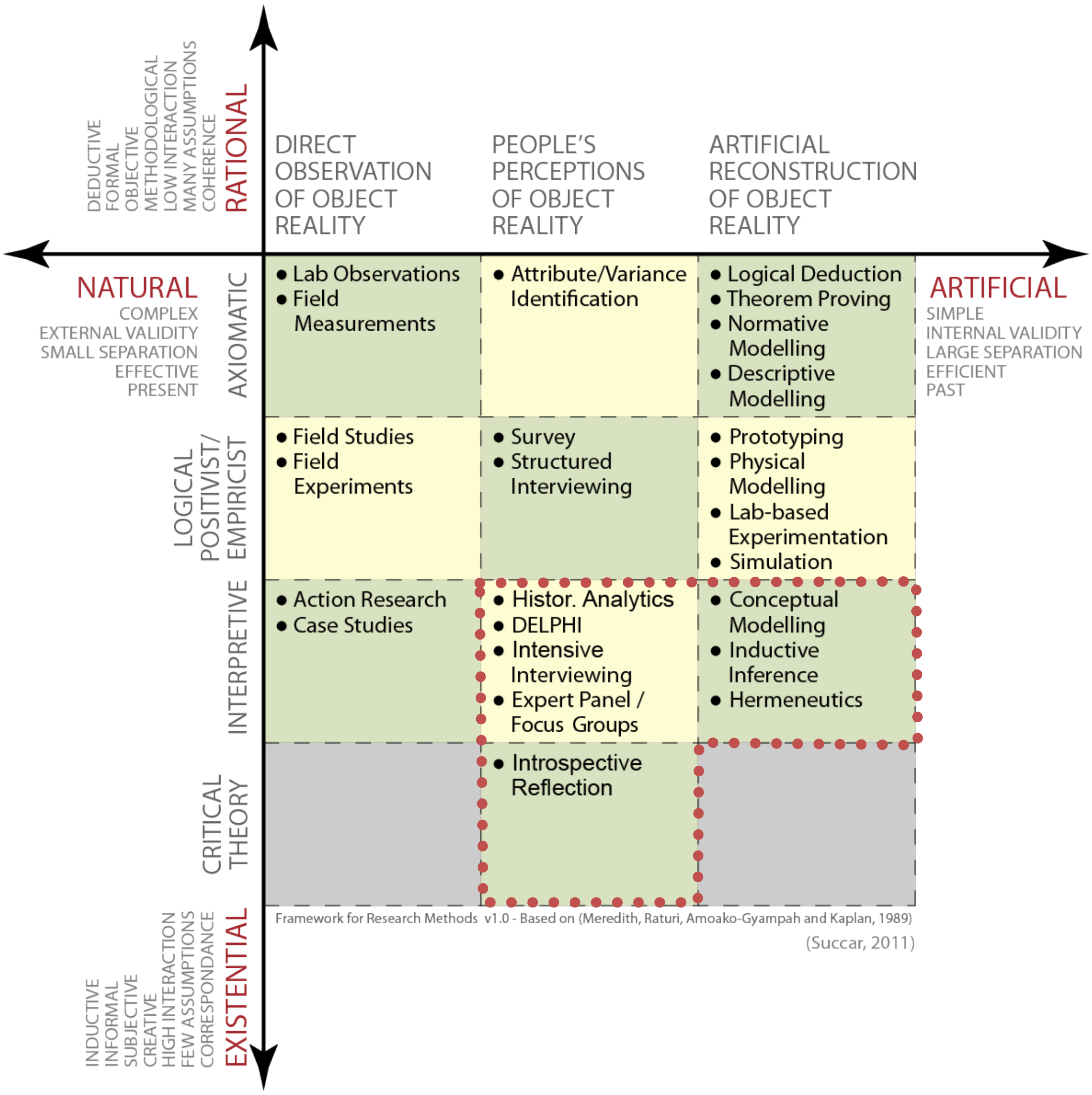

Figure 1. Framework of Research Methods – adopted from Meredith et al. (1989), the dotted polygon highlights the cells which collectively represent the research methods employed by this study

According to Downward and Mearman (2007, p. 3), the "specific nature of research questions and programmes will govern the choice of specific methods". This study employed a mixture of methods to address the research questions: in illustrating the knowledge structures underlying the BIM domain and developing the knowledge tools, conceptual modelling and Inductive Inference – methods residing within the interpretive/artificial cell of Figure 1 - were used to *describe* and *explain* the framework. However, to test the conceptual constructs – as a hypothetical representation of reality - focus groups and feedback forms were used as methods to capture subject matter expert's *perception of reality* (Meredith et al., 1989) (Mitroff & Mason, 1982).

7.4 Data collection

While qualitative approaches have been criticized for being overly subjective and lacking in replicability and generalizability, quantitative approaches have also been criticized for lacking representative validity within social – as opposed to natural - environments (Hewson, 2006). To bridge this divide, *pragmatists* argue that the research method to be used should be selected according to its instrumental value in enabling people to understand the world (Hammersley, 2006). To satisfy the hypothetical and demonstrative nature of the research questions (section 4), this study embraced a *pragmatic* approach to research design (Hammersley, 2006) (Tashakkori & Teddlie, 1998). As described below, both quantitative and qualitative data were collected from BIM subject matter experts (SME)s to calibrate knowledge constructs against SME's *perception of reality* (Meredith et al., 1989) (Mitroff & Mason, 1982).

Foundational parts of the BIM framework were first submitted for scrutiny through peer-reviewed publications (papers A1-A3, a record of citations received to date is provided in Part III - Appendix C). To reach a wider audience and capture additional feedback, the author also published and maintained a weblog[8] covering many of the concepts explored in this study. The contents of posts and peer-reviewed papers also formed a basis for several industry presentations and workshops[9] which provided additional feedback avenues.

Following this initial exploration and informal data collection, top-level framework components and a set of conceptual models were presented to subject matter experts. To represent a subset of industry stakeholders, 70 SMEs from both industry and academia were invited to participate in focus groups across three countries: the United States, the United Kingdom and Hong Kong. Each focus group included an average of 12 SMEs to "maximize the depth of expression" from each participant and "allow meaningful interaction with both the moderator and amongst themselves within the

[8] Several of the conceptual models developed as part of this study were published through BIM Thinkspace (www.BIMthinkspace.com). Starting in October 2005, the blog published a total of 26 posts in 8 years (14 post topics are directly derived from this study); attracted 1025 subscribers and 107,000 page views (as of June 27, 2013).
[9] A list is presentations and workshops is provided at http://changeagents.blogs.com/about.html

constraints of available time” (Debus, 1989, p. 13). During focus group sessions, participants discussed the framework’s components with the researcher/facilitator and amongst themselves, commented on the framework’s clarity, accuracy and usability, and whether they found value in the framework’s visual representations. A total of 63 participants also provided anonymous feedback in the form of written comments and suggestions. Analysis and discussion of the aforementioned feedback is yet to be published. For reference purposes, the structured questionnaire used during focus group sessions is provided in Part III - Appendix D.

8 Conceptual constructs

BIM is an emergent field of research and application. To facilitate BIM adoption by industry stakeholders, BIM concepts and their relationships need to be simplified, structured and described through theoretical constructs that organize domain knowledge (Reisman, 1988) (Diane, 1998). Once domain knowledge is organized, practicable knowledge tools can be developed to facilitate performance improvement.

This study delivers a *representative theoretical framework*, a construct that simplifies a complex phenomenon by identifying its concepts and their inter-relations (Dubin, 1978). The BIM framework is built upon several interrelated models, taxonomies and classifications as illustrated in Figure 2 below[10]:

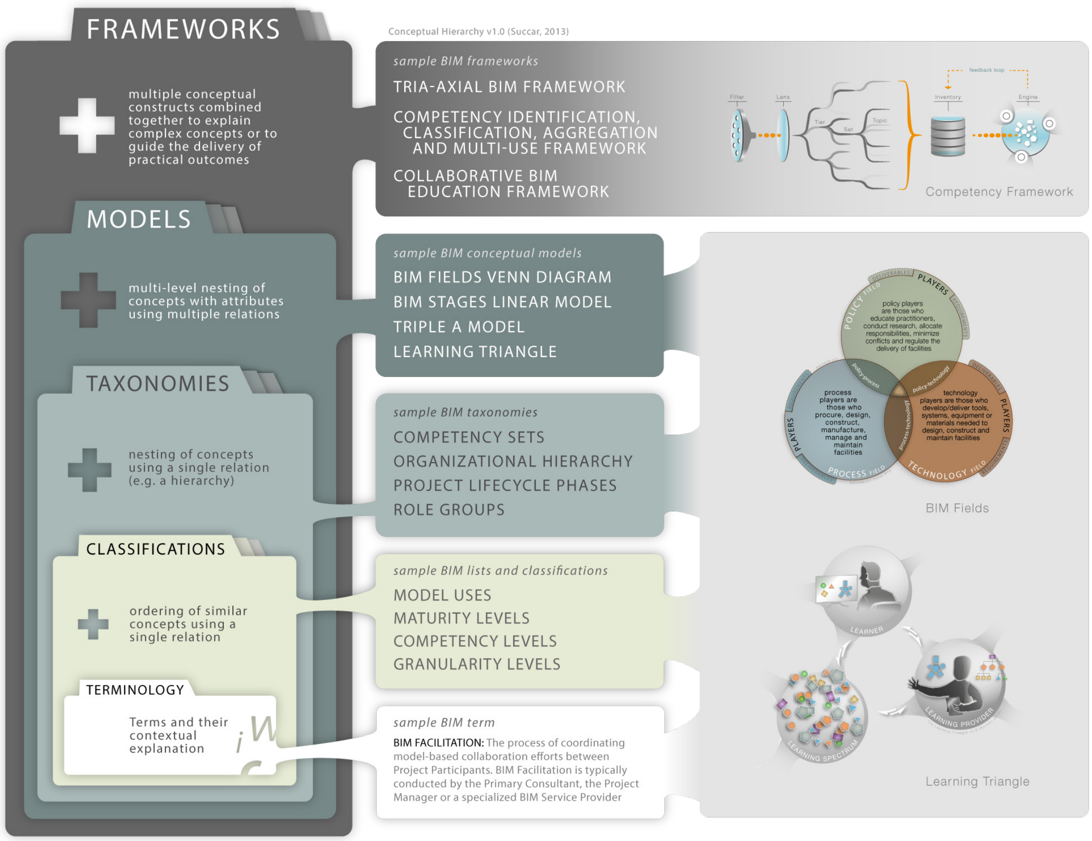

Figure 2. Hierarchy of conceptual constructs within the BIM framework

[10] The first iteration of this conceptual hierarchy was based on the 'grouped archetypes' graph by CEN (2004, p. 34) which includes 'vocabulary', 'dictionary', classification', 'taxonomy' and 'ontology'.

The next sections (8.1 - 8.5) explain the different types of conceptual constructs delivered by this study. These constructs are later identified against published papers in section 10.3 and illustrated as a conceptual and practical continuum in section 10.1:

8.1 Frameworks

According to Meredith, a framework is "essentially a pre-theory and may well substitute in many ways for a theory. That is, like theory it may identify relevant variables, classify them, describe their interactions, and allow a mapping of items (such as the existing literature or research studies) on to the framework" (Dubin, 1978, p. 7). A framework shows "the gestalt, the structure, the anatomy or the morphology of a field of knowledge or the links between seemingly disparate fields or sub-disciplines" (Reisman, 1994, p. 92).

A well-structured theoretical framework can thus assist in organizing domain knowledge, eliciting tacit expertise and facilitating the creation of new knowledge. The utility of such frameworks is articulated by Minsky (1975) who states:

> *"Here is the essence of the theory: When one encounters a new situation (or makes a substantial change in one's view of the present problem) one selects from memory a structure called a Frame. This is a remembered framework to be adapted to fit reality by changing details as necessary. A frame is a data-structure for representing a stereotyped situation... Attached to each frame are several kinds of information. Some of this information is about how to use the frame. Some is about what one can expect to happen next. Some is about what to do if these expectations are not confirmed. We can think of a frame as a network of nodes and relations." (Minsky, 1975, p. 2)*

As a network of nodes and relations, the BIM framework is continuously expanding by adding new - or refining existing - interrelated nodes: models, taxonomies, classifications and terms. The BIM framework however is primarily a three-axial structure (Figure 3) supporting all other conceptual constructs:

- X-axis: *BIM fields* of activity identifying domain players, their requirements and deliverables;

- Y-axis: *BIM stages* delineating the minimum capability benchmarks and revolutionary milestones which can be further subdivided into incremental steps to guide BIM implementation; and
- Z-axis: *BIM lenses* representing distinctive layers of analysis that – when applied to fields and stages - generate knowledge views which abstract the BIM domain and control its complexity by removing unnecessary detail (Kao & Archer, 1997). Through lenses, domain researchers can isolate particular aspects of the construction industry to generate knowledge views that either (a) highlight observables which meet the research criteria or (b) filter out those that do not.

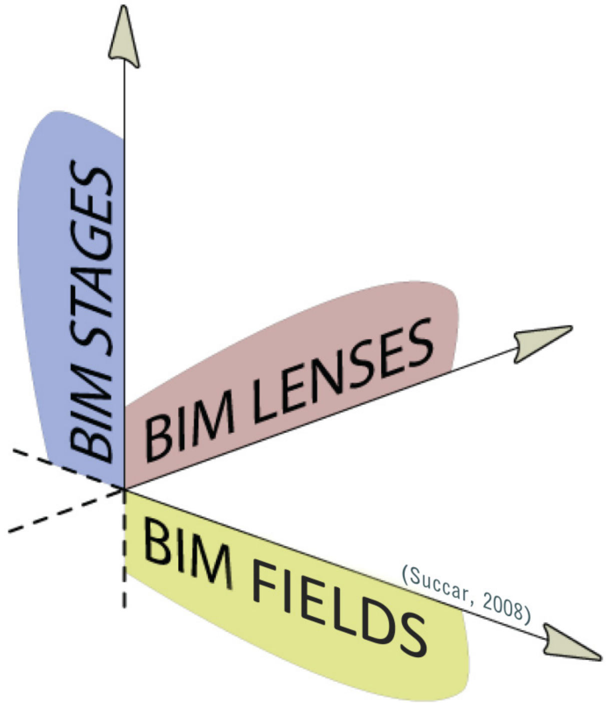

Figure 3. A tri-axial model of the BIM framework: fields, stages and lenses

The Tri-axial model representing the BIM framework (Figure 3) is a reflection of three implicit principles underlying this study. First, to understand BIM, one needs to understand its parts, their overlaps and interactions. In this respect, it is not sufficient to focus on BIM *technologies* (e.g. software, hardware, networks and data), but similar attention must be given to *processes* (e.g. leadership, knowledge and skills) and governing *policies* (e.g. contracts, standards and codes). Second, for an organization or a team to implement BIM tools and workflows, it is important to recognize both revolutionary stages and incremental steps. While these capability stages and implementation steps may include a large number of activities and respective resources, these – with the appropriate knowledge constructs and tools - can be both quantified and qualified. Third, to reduce BIM domain complexity, it must be analysed using multiple lenses; each revealing a manageable part of the overall knowledge landscape. Using lenses allows a focused analysis of a specific discipline (e.g. architecture, engineering or facility management), a certain scale (e.g. market, organization or individual), or a particular conceptual part (e.g. equipment, tasks or benefits), yet without severing ontological connections to larger constructs or to other disciplines, scales and conceptual parts.

8.2 Models

Models are simplified representations and abstractions of the "enormous richness of this world" (Ritter, 2010, p. 360) (Lave & March, 1993). A good model, according to Ritter (2010, p. 349), "provides a more *condensed* representation of what was originally given". It contributes to knowledge sharing by reducing complexity and ambiguity, and – as a result - makes "insights more portable between people". For a model to accurately represent a phenomenon, the model-builder needs to judiciously identify (a) how observations/data are to be condensed into the model without losing any essential attributes of the phenomenon, and (b) how to identify the right level of simplicity/complexity to be built into the model so it *facilitates understanding* of the phenomenon (Ritter, 2010). As opposed to *mathematical* or *statistical* models (Reisman, 1988) which represent data and their relationships, a *conceptual model* includes a set of concepts, "characteristics associated with certain events, objects, or conditions […to] represent or describe (but not explain) an event, object, or process" (Meredith, 1993, p. 5).

Several models were developed as part of this study to represent complex concepts and facilitate their understanding. Some of these models are descriptive (e.g. the Venn diagram representing interlocking BIM fields – papers A1-A3), some are predictive (e.g. the model representing the effects of BIM on project lifecycle phases - paper A2) while others are instructive – explaining the sequence of actions to be followed to achieve a pre-defined outcome (e.g. the workflow model representing competency identification, classification, aggregation and use - paper A6).

8.3 Taxonomies

Taxonomies are an efficient and effective way to organize and consolidate knowledge (Reisman, 2005) (Hedden, 2010). A well-structured taxonomy allows "the meaningful clustering of experience" (Kwasnik, 1999, p. 24). In developing specialized taxonomies to organize BIM domain knowledge, this study adopted the guidelines introduced by Vogel and Wetherbe (1984) and Gregor (2006). That is, a taxonomy is expected to be "complete and exhaustive; [includes] classes that encompass all phenomena of interest; [is based on] decision rules, [which are] simple and parsimonious to assign instances to classes; and the classes should be mutually exclusive. In addition, as taxonomies are proposed to aid human understanding, [these classes should be] easily understood and [...] appear natural" (Gregor, 2006, p. 619).

This study delivers several BIM-specific taxonomies to clarify the knowledge structures underlying the BIM domain and facilitate the development of conceptual models and performance improvement tools. For example, the *organizational hierarchy*, *BIM competency hierarchy* and *BIM knowledge content* taxonomy (papers A3, A6 and B1 respectively) are conceptual constructs to support performance assessment of individuals, organizations and *whole markets* (paper B1 compares the BIM maturity of 8 countries based on their noteworthy BIM publications). Each of these taxonomies are "a means toward a number of different ends; one of these ends is providing direction and/or guidance to expansion or generalization of knowledge" (Reisman, 1988, p. 216).

8.4 Classifications

Classification is the "meaningful clustering of experience" (Kwasnik, 1999, p. 24) and "lies at the heart of every scientific field" (Lohse, Biolsi, Walker, & Rueter, 1994, p. 36). Classification is also a heuristic tool useful during the formative stages of discovery, analysis and theorizing (Davies, 1989). For example, when reviewing existing literature, classification is a simple method to organize concepts and allow patterns to emerge (Diane, 1998).

This study delivers several classifications to support the development of conceptual models. Some of these classifications have been adopted from other fields and then customized to suit the specific requirements of this study. For example, the *BIM maturity level classification* is an amalgamation of several maturity levels from across the construction and software industries (paper A3). Also, new classifications were developed to meet the particular requirements of this study. For example, the *BIM granularity levels* classification has been developed to separate low-detailed BIM capability self-assessments from highly-detailed, professionally-delivered BIM maturity audits (paper A3). Each of these classifications provides a foundation for multiple taxonomies and conceptual models. For example, *model uses* - the deliverables expected from using BIM tools - is a classification used to populate several taxonomies and conceptual models including *organizational requirements* (taxonomy), *team deliverables* (taxonomy) and *project workflows* (conceptual model – paper A6, Figure 9).

8.5 Dictionaries

A dictionary is a “reference source in print or electronic form containing words usually alphabetically arranged along with information about their forms, pronunciations, functions, etymologies, meanings, and syntactical and idiomatic uses” (Merriam-Webster, 2013 - Item 1). Dictionaries are a collation of terms and their definitions and form the foundations of larger knowledge structures – classifications, taxonomies and conceptual models.

Throughout this study, a list of commonly used BIM terms were investigated and used. A large number of these were later collated into a cohesive *BIM dictionary* that eliminates conflicting definitions; identifies synonyms; and allows classifications and taxonomies to be consistently formulated. Delivered through a dedicated online tool under a Creative Commons 3.0 license, the BIM dictionary is a *web of meaning* (Cristea, 2004) connecting terms to each other and to other knowledge bases. As of June 2013, the BIM dictionary included more than 370 interlinked BIM terms and their research-based definitions (BIMe, 2013). A sample of these terms is provided in paper A6 –Table 5.

8.6 Ontologies

Ontologies are "content theories about the sorts of objects, properties of objects, and relations between objects that are possible in a specified domain of knowledge. They provide potential terms for describing our knowledge about the domain" (Chandrasekaran, Josephson, & Benjamins, 1999, p. 20). According to Van Heijst, Schreiber, and Wielinga (1997, pp. 192-193), there are several types of ontologies including *application*, *domain*, *generic* and *representation* ontologies. Domain ontologies play an important role in acquiring, analysing and reusing domain knowledge by making implicit assumptions explicit and facilitating communication between people (Milton, 2007a) (Milton, 2007b) (Cottam, 1999) (Noy & McGuinness, 2001) (Studer, Benjamins, & Fensel, 1998). Through ontologies, domain concepts and their relationships can be interdependently formalised through knowledge acquisition, introspection and representation which, in turn, can form a basis for additional knowledge acquisitions (Holsapple & Joshi, 2006).

The BIM ontology is intended as a *domain vocabulary* (Chandrasekaran et al., 1999) for representing BIM concepts and their relationships; facilitating knowledge acquisition from subject matter experts; and sharing domain knowledge. The BIM ontology is discussed in detail in Part III - Appendix A.

9 Framework development

According to Meredith (1993), theory building – from models through frameworks to theories - is an iterative process passing through *three repetitive stages*: description, explanation and testing (Meredith, 1993) (Meredith et al., 1989). The three stages are briefly explored below:

- The *description stage* develops a description of reality; identifies phenomena; explores events; and documents findings and behaviours. According to Dubin (1978, p. 85):

> *"In every discipline, but particularly in its early stages of development, purely descriptive research is indispensable. Descriptive research is the*

stuff out of which the mind of man, the theorist, develops the units that compose his theories. The very essence of description is to name the properties of things: you may do more, but you cannot do less and still have description. The more adequate the description, the greater is the likelihood that the units derived from the description will be useful in subsequent theory building."

- The *explanation stage* builds upon descriptions to *infer* a concept, a conceptual relationship or a construct; and then, develops a framework or a theory to explain and/or predict behaviours or events. *Explaining* is the process of (a) identifying a phenomenon's purpose, (b) showing that a new phenomenon is an instance of a familiar phenomenon <u>or</u> (c) positioning a new phenomenon under an existing or new law (Meredith et al., 1989). In essence, the *explaining stage* develops a testable theoretical proposition which clarifies what has previously been described.
- The *testing stage* inspects explanations and propositions for validity; tests concepts or their relationships for accuracy; and tests predictions against new observables.

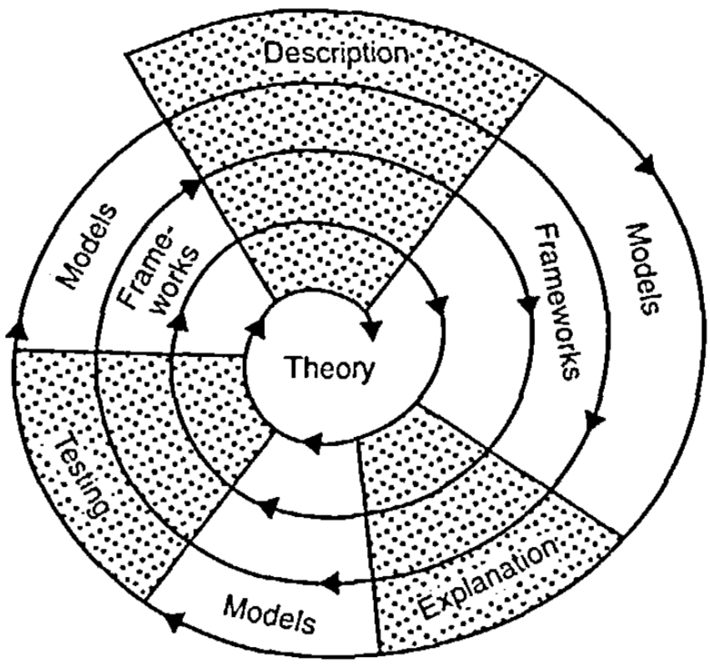

Figure 4. The *Normal Research Cycle* (Meredith, 1993 - Page 4)

The three stages (Figure 4) are *cyclical* as the process of testing concepts and theoretical propositions necessitates the collection of additional descriptions; which generate new concepts and/or modify existing ones; and which, in turn, require additional testing (Meredith et al., 1989). As discussed below, the three theory-building stages are all required to generate understandable and usable models, frameworks or theories that can describe, explain and predict reality:

- If the description stage is omitted, the theoretical proposition developed by researchers is not based on observation or field data. The propositions will then lack external validity yielding a research result which is "disconnected from the real world and irrelevant to the reality of the problems […] These findings we 'call ivory-tower prescriptions'" (Meredith, 1993, p. 4);
- If the explanation stage is omitted, the research iterates between describing and testing thus yielding no new models, frameworks or theories. With the absence of explanation, only explanatory models - which can only simulate reality without explaining it - can be generated. Also, without proper explanation, the theoretical proposition cannot be understood and is thus unlikely to be adopted; and
- If the testing stage is omitted, the research alternates between describing observables and explaining them yet without validating these propositions. Without testing, theoretical propositions can be discounted as anecdotal, unreliable, and thus unsuitable to build additional research.

This study adopted a similar cyclical path to that described by Meredith (1993) - from describing; to explaining; to testing; and then back to describing. First, a *description* of the BIM domain was generated through a process of inductive inference (Michalski, 1987), conceptual clustering (Michalski & Stepp, 1987) and reflective learning (Van der Heijden & Eden, 1998) (Walker, Bourne, & Shelley, 2008). Second, a theoretical framework was developed to visually *explain* the knowledge structures underlying the BIM domain. Third, the BIM framework and many of its constituent models were *tested* through focus groups and peer-reviewed publications.

The adoption of this three-staged approach for developing the BIM framework and its conceptual models is not only consistent with Meredith (1993) but it reflects the retroductive research strategy underlying this study (section 7.27.2.4). In developing a theoretical model, retroduction follows a similar three-step approach: first, “the research starts in the domain of actual, by observing connections between phenomena […]. To do so, as a second step, researchers build a hypothetical model, involving structures and causal powers located in the domain of real, which, if it were to exist and act in the postulated way, would provide a causal explanation of the phenomena in question. The third step is to subject the postulated explanation to empirical scrutiny” (Leca & Naccache, 2006, p. 635).

10 Research deliverables

This section first lists and then summarizes the contents of three types of papers included as part of this submission:

- Type A includes six published peer-reviewed papers (A1-A6) with the candidate being the sole or primary author;
- Type B includes two peer-reviewed papers (B1 and B2) with the candidate being the second author. Paper B1 has been accepted for publication (but not yet published) while paper B2 is under review (no acceptance note issued); and
- Type C includes a single published peer-reviewed paper composed of three complementary documents. The candidate played a primary role in authoring and paper C which includes several co-authors, and forms part of a collaborative effort between industry and academia.

As will be clarified in section 10.2, the contributions made by the candidate within these papers are complementary and collectively form the unified deliverables of this study.

10.1 List of included papers

This section lists the nine papers (in three types) constituting this thesis by publication:

Paper A1 **Succar, B.**, Sher, W., & Aranda-Mena, G. (2007). A proposed framework to investigate Building Information Modelling through knowledge elicitation and visual models. Paper presented at the Australasian Universities Building Education (AUBEA2007), Melbourne, Australia.

Paper A2 **Succar, B.** (2009). Building information modelling framework: a research and delivery foundation for industry stakeholders. *Automation in Construction, 18*(3), 357-375.

Paper A3 **Succar, B.** (2010). Building Information Modelling maturity matrix. In J. Underwood & U. Isikdag (Eds.), *Handbook of research on Building Information Modelling and construction informatics: concepts and technologies* (pp. 65-103): Information Science Reference, IGI Publishing.

Paper A4 **Succar, B.** (2010). *The five components of BIM performance measurement*. Paper presented at the CIB World Congress, Salford, United Kingdom.

Paper A5 **Succar, B.**, Sher, W., & Williams, A. (2012). Measuring BIM performance: five metrics. *Architectural Engineering and Design Management, 8*(2), 120-142.

Paper A6 **Succar, B.**, Sher, W., & Williams, A. (2013). An integrated approach to BIM competency acquisition, assessment and application. Automation in Construction, doi: http://dx.doi.org/10.1016/j.autcon.2013.05.016 (Published online, In Press).

Paper B1 Kassem, M., **Succar, B.**, & Dawood, N. (2014). Building Information Modeling: analyzing noteworthy publications of eight countries using a knowledge content taxonomy In R. Issa & S. Olbina (Eds.), *Building Information Modeling: applications and practices in the AEC industry*. University of Miami: ASCE. (Approved for publication).

Paper B2 Kassem, M., **Succar, B.**, Dawood, N. (2013). *A proposed approach to comparing the BIM maturity of countries*. CIB W78 2013, 30th international Conference on applications of IT in the AEC industry, 9-12 October 2013, Beijing, China.

Paper C **Succar, B.**, Agar, C., Beazley, S., Berkemeier, P., Choy, R., Rosetta Di Giangregorio, Donaghey, S., Linning, C., Macdonald, J., Perey, R., & Plume, J. (2012). BIM in Practice - BIM Education, a position paper by the Australian Institute of Architects and Consult Australia. http://www.bim.architecture.com.au/

10.2 Content summary of included papers

This section summarizes the research deliverables of papers listed in section 10.1. It discusses how each paper relates to other papers and contributes towards addressing the research questions identified in section 4:

Paper A1 **A Proposed Framework to investigate Building Information Modelling through knowledge elicitation and visual models** (Succar, Sher, & Aranda-Mena, 2007)

Paper A1 is the first article developed as part of this study. It briefly introduced the BIM term, proposed a prototypical framework and suggested an investigative methodology to identify, capture and represent BIM interactions. The paper then identified ontology-supported visual models as a means to elicit and organize expert knowledge, compared the terms ‘information visualization’ and ‘knowledge visualization’, and identified the latter as an appropriate method to represent BIM interactions. This paper played an important role in establishing the need for an overarching BIM framework, the necessity for an underlying BIM ontology and the importance of knowledge visualization for eliciting and representing domain knowledge.

Paper A2 **Building information modelling framework: a research and delivery foundation for industry stakeholders** (Succar, 2009)

This scene-setting paper extended the prototypical BIM framework introduced in paper A1. Two new conceptual dimensions where added and the BIM framework now represented three main interconnected components (fields, stages, and lenses). In addition to reviewing a number of noteworthy BIM publications (e.g. BIM guides), this paper established several principles upon which this study revolves including - including:

- The BIM domain is complex and requires a structured approach to organize its underlying knowledge, facilitate its implementation, and bridge the chasm separating academic from industrial understandings of BIM;
- The BIM domain can be understood by capturing the interactions and overlaps between three main different types of players and their respective deliverables and requirements;
- BIM diffusion within organizations and across markets, its effect on project lifecycle phases, and the myriad of steps needed to improve performance can be understood and measured through revolutionary stages and evolutionary steps;
- The complexity of the BIM domain can be represented through the careful application of distinctive layers of analysis (referred to as BIM lenses and filters) which remove unnecessary detail and isolate the knowledge areas requiring attention;
- To capture and represent complex BIM concepts and their relationships, a specialized domain ontology is needed; and
- To share BIM knowledge with a wide audience, a visual language is required.

In summary, most concepts, models and taxonomies - developed in subsequent papers, and submitted as part of this study - are based on the principles introduced in this paper.

Paper A3 **Building Information Modelling maturity matrix** (Succar, 2010a)

This paper builds upon the principles and conceptual deliverables of paper A2 to introduce additional models and taxonomies. These were then used to generate practicable tools that can be used by organisations and project teams to assess their own BIM ability. In addition to an extended literature review covering existing maturity models, performance excellence and quality management frameworks, this paper delivered the following:

- A conceptual differentiation between BIM capability and BIM maturity to enable two unique yet complementary types of assessment;
- BIM competency sets to be used for assessment and implementation;
- An organisational scale, a taxonomy for tailoring capability/maturity assessments to suit varied organisational sizes – from markets and industries, through organizations and teams, to individual members;
- The BIM Maturity Index (BIMMI) to be used in measuring BIM maturity - the quality and repeatability of BIM abilities;
- A granularity index for tailoring BIM tools, guides and reports to suit different levels of assessment detail;
- A low-detail, maturity assessment scoring system; and
- The BIM Maturity Matrix, a static performance measurement and improvement tool that identifies the correlation between BIM stages, competency sets, maturity levels and organisational scales.

In summary, this paper introduced a practicable tool derived from the BIM framework's components. Its indices and taxonomies – applied in A3 to measure the BIM performance of organizations and teams - were later extended and applied to smaller (individuals - refer to paper A6) and larger organizational units (countries - refer to papers B1 and B2).

Paper A4 **The Five Components of BIM performance measurement** (Succar, 2010b)

This paper summarizes the research conducted and the conceptual constructs generated in paper A3. It also introduces a new conceptual model explaining the role BIM fields, stages and lenses play in generating BIM competency sets (Fig 3 in paper A4). Another deliverable of this paper is the simplified correlation of five BIM framework components (capability stages, maturity levels, competency sets, organisational scales, and granularity levels) for the purpose of performance measurement. In summary, this paper positions the framework and its many components as a theoretical – as well as practical - structure for assessing and improving BIM performance *within* and *across* different organizational scales.

Paper A5 **Measuring BIM Performance: five metrics** (Succar, Sher, & Williams, 2012)

This paper further explores the conceptual background underpinning BIM performance assessment and includes an updated review of BIM maturity frameworks which emerged since the BIM Maturity Matrix chapter was published (paper A3). The paper then discusses the five BIM performance assessment metrics; how they complement each other; and how they jointly enable targeted performance analyses through a simple assessment workflow. In summary, this paper further solidifies the arguments surrounding BIM performance assessment of organizations and teams, and identifies future practical applications for these assessments.

Paper A6 **An integrated approach to BIM competency assessment, acquisition and application** (Succar, Sher, & Williams, 2013)

This paper expands upon previously published papers covering organizational capability, to focus on individual competencies as the building blocks of organizational ability. Several additional taxonomies and conceptual models were introduced to extend the applicability of the BIM framework, from assessing organizations and teams (papers A3-A5), to their human ingredient. The main deliverables of this paper can be summarized as follows:

- The introduction of several taxonomies and conceptual models including: units of analysis, competency manifestations, competency levels, and a tiered taxonomy of individual BIM competencies;
- The introduction of a flow-model describing how competency items can be identified, classified, aggregated and used;
- The introduction of a knowledge engine to generate integrated assessment components, learning modules and process workflows; and
- The introduction of a prototypical online assessment tool linked to a BIM dictionary and e-learning modules (Figure 10).

In summary, this paper extends the BIM framework's coverage to individuals, the smallest organizational units. It thus widens this study's conceptual platform and facilitates the future development of multi-scale assessment, learning and performance improvement tools.

Paper B1 **Building Information Modeling: analyzing noteworthy publications of eight countries using a knowledge content taxonomy** (Kassem, M., Succar, B., Dawood, N., 2014) (accepted for publication June 25, 2013)

This paper reviews 55 noteworthy BIM publications (NBP)s from across 8 countries and analyses their knowledge content using a BIM knowledge content (BKC) taxonomy. The NBP definition and BKC taxonomy are both derived from the conceptual constructs developed as part of this study:

- The delimitation of noteworthy BIM publications is derived from the interaction between BIM fields and BIM lenses (refer to paper A2); and
- The BIM knowledge content (BKC) taxonomy is a filtered representation of the BIM policy field – please refer to Part III, Appendix B.

In summary, the main deliverables of this paper - a collaborative effort with other researchers – support and extend this study as follows:

- Extends the literature review conducted in paper A2 to cover new noteworthy BIM publications;
- Tests the applicability of the BIM framework in generating new knowledge structures to suit varied research aims; and
- Adapts framework taxonomies to investigate and identify new knowledge gaps within the BIM domain.

Paper B2 **A proposed approach to comparing the BIM maturity of countries** (Kassem, M., Succar, B., Dawood, N., 2013)

This paper builds upon the literature reviewed within paper B1 to propose three new, country-scale BIM maturity metrics. These metrics are intended to augment BIM adoption data typically collected through survey tools, by measuring the availability of noteworthy BIM publications (NBP)s, their distribution across different BIM knowledge contents (BKC, refer to Part III - Appendix B) and the perceived relevance of each NBP in addressing a specific BIM topic. This paper makes two main contributions to this study:

- Introduces a 5-level metric to assesses the relative relevance of noteworthy BIM publications; and
- Applies the study’s conceptual constructs in assessing - in addition to organizations, teams and individuals (papers A3-A6) - the BIM maturity of countries.

Paper C **BIM in Practice - BIM Education, a position paper by the Australian Institute of Architects and Consult Australia** (Succar, Agar, Beazley, Berkemeier, Choy, Giangregorio, Donaghey, Linning, Macdonald, Perey, & Plume, 2012)

This position paper stems from the efforts of the BIM Education Working Group (EWG), part of the Australian Institute of Architects and Consult Australia BIM/IPD initiative. The EWG included eleven members from industry (practicing professionals) and academia (university/TAFE lecturers and researchers). The paper delivered as a result of this collaborative effort included three complementary documents that identified *BIM learners* and their varied requirements; explored BIM le*arning providers* and the current status of BIM education; defined the *BIM learning spectrum*; and generated a draft *collaborative BIM education framework*. The dedicated framework, the knowledge structures – namely BIM competencies and sample educational deliverables – are derived from the research conducted for paper A6.

Declaration: I hereby certify that this paper has been done in collaboration with other researchers and conducted under the auspices of the BIM/IPD Steering Group of the Australian Institute of Architects and Consult Australia. My contributions to this effort – as a working group Chair and the main author of the BIM Education documents - have been delivered as an unpaid volunteer.

10.3 Research themes across included papers

Table 2 below explores the common research themes across papers submitted as part of this thesis by publication. It lists the literature reviews conducted, the research methodology used and the distribution of conceptual constructs and practicable tools across papers. The table highlights the step-wise progression from foundational, conceptual work to practicable research deliverables:

Table 2. Study deliverables across the nine papers

	A 1	A 2	A 3	A 4	A 5	C	A 6	B 1	B 2	Introduct. document
Literature reviews										
Available frameworks		○						●	○	
Competency connotations							○			
Knowledge visualization principles	○	●								
Performance measurement models			○		●			○		
Research methodology										
Conceptual background		○			○					●
Framework development methodology	○									●
Research design	○	○								●
Underlying theories										○
Conceptual constructs										
BIM Framework + Tri-axial model	○	●	●	○	○		●	○	○	
BIM fields	○	●	○		●					
Players	○	●								
Deliverables	○	●								
Requirements			○		○					
Overlaps		○	○							
Interactions	○	●	○							
BIM lenses and filters		○	○							
BIM capability stages		○	●	○	○			○	○	
BIM ontology		○								●
Collaborative BIM Education Framework						○				
Competency approaches							○			
Competency components + manifestations							○			
Competency sets		○	●	●	●		●			
Competency units of analysis							○			
Granularity levels			○	○	○			○		
Individual competency classes and sub-classes							○			
Organizational hierarchy and scales			○	○	○		○	○	○	
Knowledge content taxonomy								○		○
Project lifecycle phases		○								
Seed competency inventory						○	●			
Triple A competency + competency flow models							○			
BIM acquisition + BIM learning Modules						○	●			
BIM application + sample BIM workflow							○			
BIM assessment + assessment workflow			○	●	○		●			
Practicable knowledge tools										
BIM dictionary, online module							○			
BIM maturity index (BIMMI)			○	○	○		○	○	○	
BIM maturity matrix (BIm^3)			○							
Individual competency assessment, online tool							○			
Individual competency index (ICI)							○			
Noteworthy BIM publications – relevance (R-metric)									○	●
Organizational capability/maturity score			○	○	○			○	○	

Legend: ○ indicates topic mentioned within publication ● indicates topic improved upon previous published version

Notes: BIM fields and BIM players where termed BIM nodes and BIM participants respectively in paper A1
BIM capability stages where interchangeably called BIM maturity stages in paper A2
The term viDCO replaced the term IPD – as used in A2 and A3 – starting in paper A4

10.1 An expansive research continuum

The deliverables of this study are a product of multiple *interwoven research paths* forming an *expansive research mesh*. This mesh was first initiated through *describing*, *explaining* and *testing* (section 10) a small number of interconnected conceptual constructs; using test results to refine initial constructs and develop new ones; and then repeating the cyclical process to continually solidify and expand the mesh. This study thus delivers – in addition to multiple conceptual constructs and practicable tools - an *expansive research continuum*. To clarify this deliverable, three visual knowledge models (VKM)[11] have been developed:

- A Study Timeline (Figure 5) identifying the study's basic chronology and published deliverables;
- A Research Path (Figure 6) identifying the study's major milestones along four research sub-paths: literature review, research methodology, conceptual development and data collection. This VKM also identifies a number of future research activities pursuant to each research sub-path; and
- A Research Continuum (Figure 7) representing the study's network of conceptual and practical deliverables across submitted publications. The continuum highlights how each paper delivers a number of conceptual constructs which either extend earlier constructs/tools or support the development of new ones. Constructs are hierarchical (refer back to Figure 2) yet interconnect through explicit ontological *relations* (refer to Appendix A). For example, this VKM clarifies how *noteworthy BIM publications* (a dictionary term defined in paper B1, 2013) and the *BIM Maturity Matrix* (a practical tool introduced in paper A3, 2010) are ontologically-connected to constructs published within papers A1 and A2 (2007 and 2009 respectively).

[11] Please note that *conceptual models* and *visual knowledge models* are not synonymous. A conceptual model is an abstraction of reality (refer back to Section 8.2) and may not necessarily have a visual representation (e.g. a personal mental model). A visual knowledge model (VKM) however refers to the *visual language* (e.g. data graphs, workflow charts or Venn diagrams) used in representing mental models and other conceptual constructs – be it a classification, taxonomy, framework or theory. VKMs are extensively used throughout this study and have been discussed within paper A1 – the first publication.

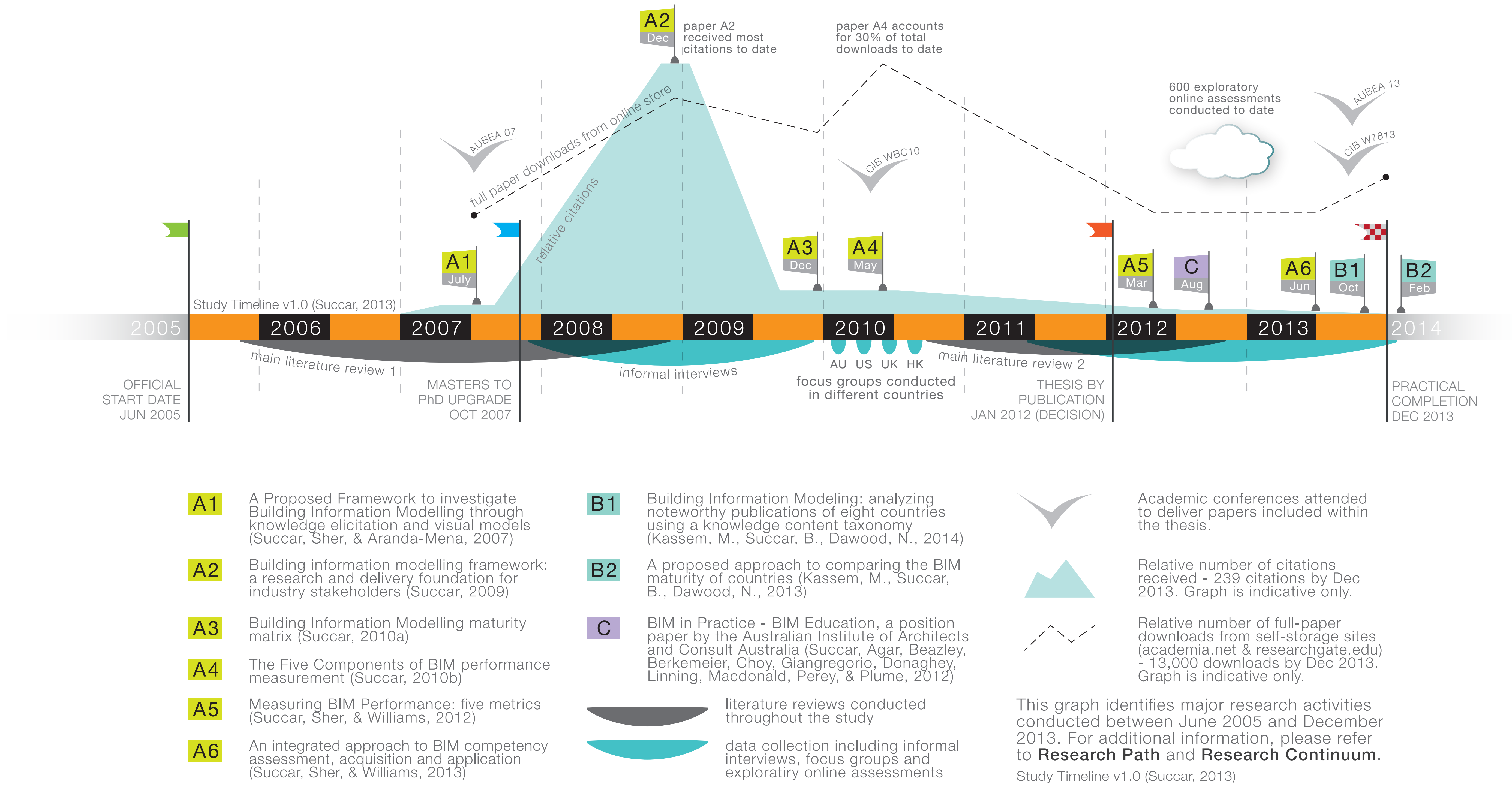

Figure 5. Study Timeline v1.0

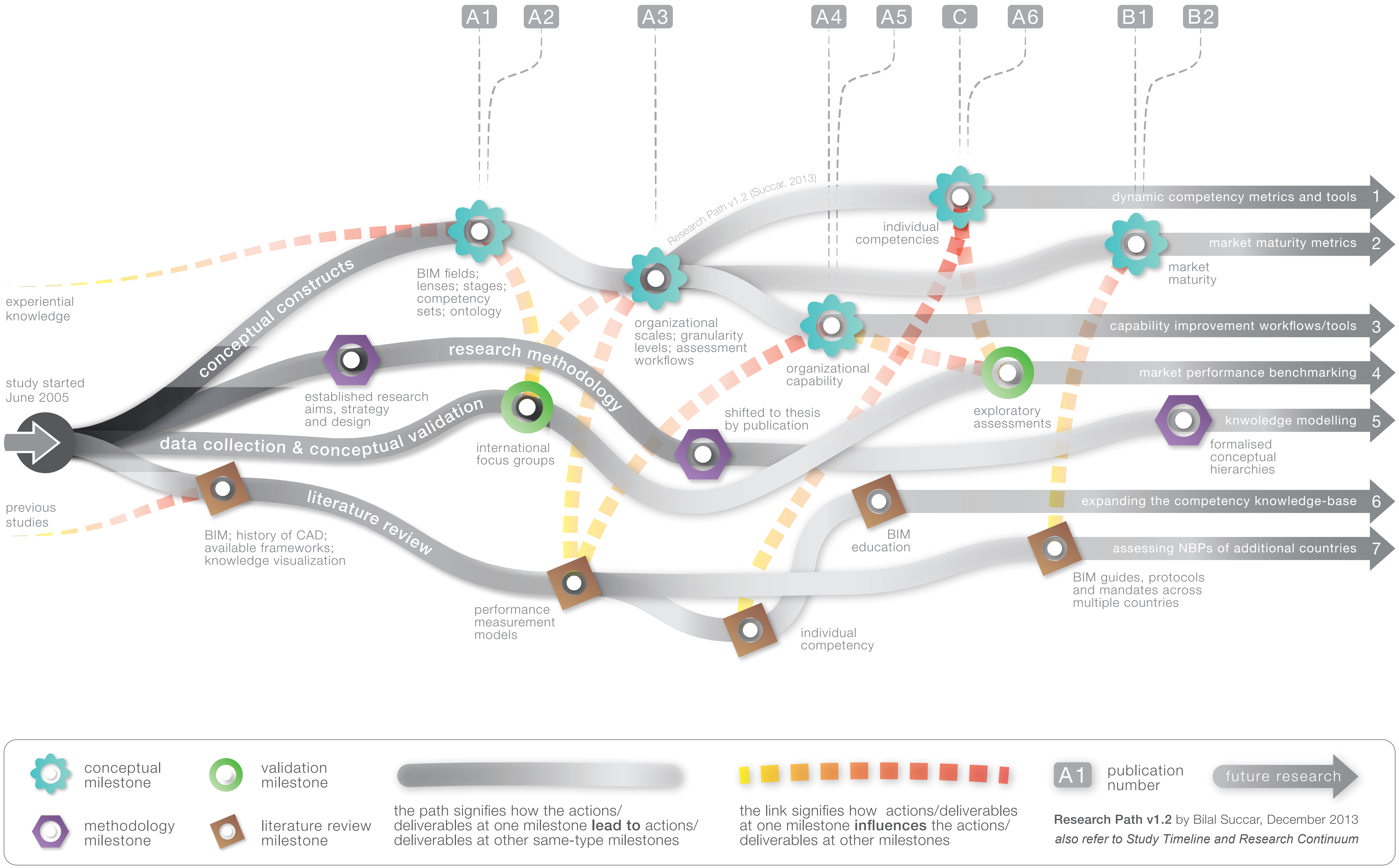

Figure 6. Research Path v1.2

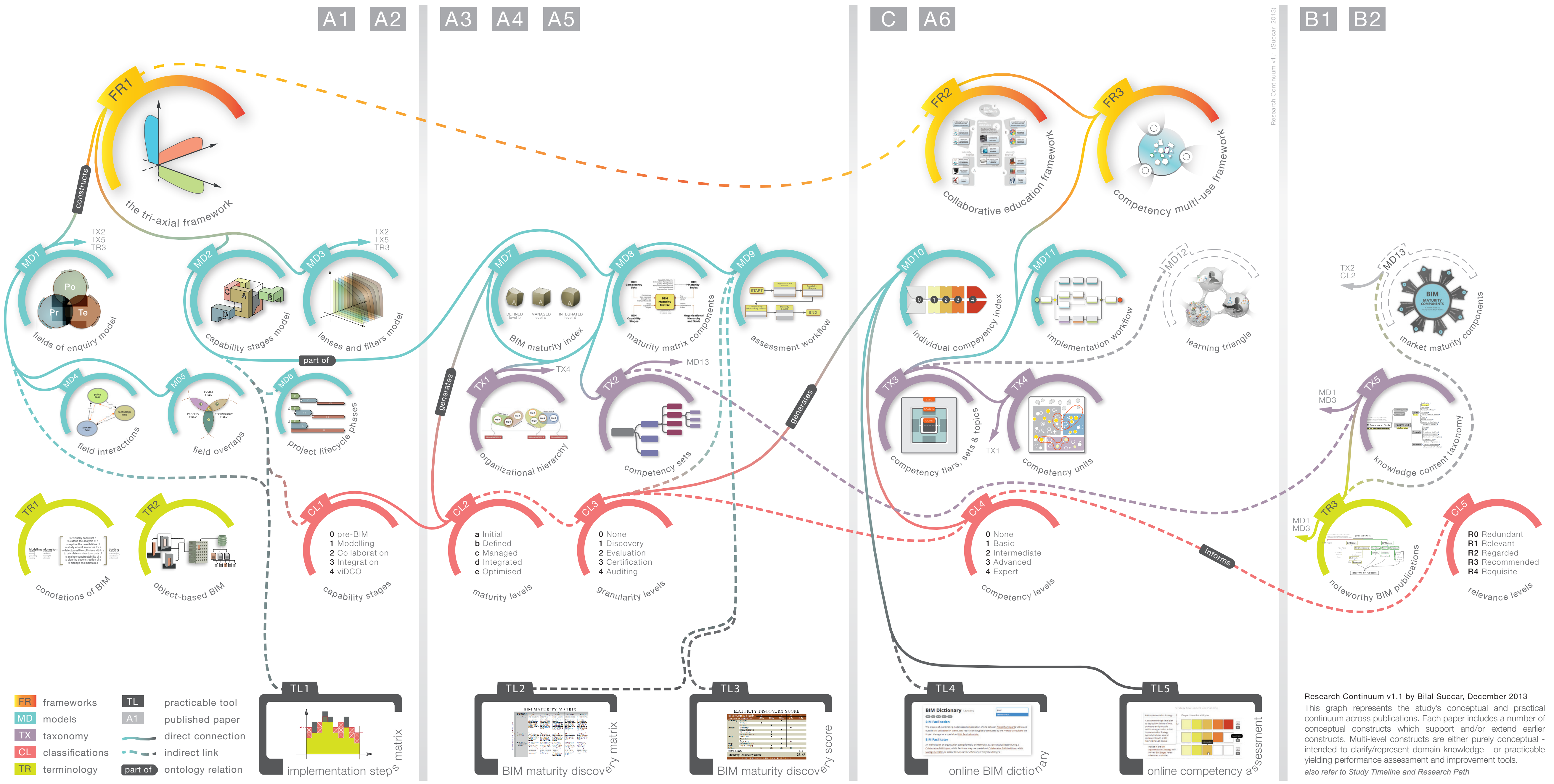

Figure 7. Research Continuum v1.1

11 Conclusion

This study is an expression of two complementary research questions: *what are the knowledge structures underlying the BIM domain*; and, *how can these knowledge structures be harnessed to assist industry stakeholders to adopt BIM or improve their BIM performance*? The first question explores the knowledge structures underlying the BIM domain whilst the second probes how these knowledge structures can be used to improve the BIM performance of industry stakeholders.

These two research questions have been addressed through the development of new conceptual constructs (e.g. classifications, taxonomies, models, an ontology and a framework) which collectively illustrate the knowledge structures underlying the BIM domain; and through the introduction of a set of tools and workflows that facilitate BIM assessment, learning and performance improvement.

The next sections briefly discuss the study's current limitations, future extensions, and provides a succinct summary of its deliverables.

11.1 Current limitations

This study has been limited by the number of testing cycles (section 8.6) performed to date. While 63 subject matter experts participated in focus groups in 2010, and more than 300 online users have since participated in exploratory competency assessments, these numbers – while statistically representative - are thinly spread across the framework's many models and tools. Collection of additional data is required before data saturation (Glaser & Strauss, 1967) (Morse, 1995) can be reached and purposeful data analyses can be conducted.

To address this limitation, a new set of focus groups will be conducted to test and validate the study's models and tools. Also, as indicated by exploratory research, a significant amount of meaningful data can be collected through the online assessment tool (prototype shown in paper A6, Figure 10). This additional primary data can then be amalgamated with the data collected in 2010, comprehensively analysed and duly published.

11.2 Future extensions

Using the BIM framework as a theoretical structure, several constructs delivered by this study will be extended, new constructs generated, and additional tools developed. Below is a succinct list of planned extensions:

- Based on assessment metrics developed in papers A3-A6 serving varied *organizational scales* (refer to paper A3), a multi-assessment framework is currently being developed to amalgamate the results of different assessment types (e.g. individual competency with organizational maturity);
- Extending the *seed competency inventory* introduced in paper A6, additional competency items will be generated to populate a specialized online platform (currently hosts more than a thousand competency items). Using a dedicated online module and - in collaboration with industry associations - assessments will be conducted to generate industry-wide BIM competency benchmarks;
- Based on the sample competency-based workflow introduced in paper A6 (Figure 9), a custom version of Business Process Model and Notation (Muehlen & Recker, 2008) (OMG, 2013) will be developed. The customised notation will benefit from

the terminology defined within the BIM dictionary and the concepts, relationships, and attributes defined by the BIM ontology (refer to Part III - Appendix A) to capture and visually represent complex BIM workflows. Combining a visually-accessible process modelling language with well-defined terms and a specialized ontology will facilitate the development of *competency-based workflows*. These can be used by industry stakeholders to guide BIM implementation and collaboration;

- The *BIM competency hierarchy* (introduced in paper A6) will be extended into a BIM *competence ontology* (Draganidis, Chamopoulou, & Mentzas, 2006) (Hirata, Ikeda, & Mizoguchi, 2001) that matches widely adopted definitions and metadata standards (IMS, 2002) (IEEE, 2008). This is intended to facilitate coordinating the BIM competence ontology with other competence ontologies covering varied knowledge domains;
- The *online BIM Dictionary* (introduced in paper A6) will be expanded to include additional terms and descriptions (currently includes 370 terms). An expanded dictionary will contribute to further reducing term ambiguity and enable the development of interconnected competency assessments, learning modules and performance workflows;
- The *competency identification, classification, aggregation* and *multiuse* model (Figure 5 of paper A6) will be developed into a framework with the addition of new taxonomies and classifications. This is intended to facilitate the identification new sets of BIM competencies across different disciplines, specialities and markets;
- The *collaborative BIM education framework* introduced in paper C will be extended with additional taxonomies and conceptual models. This is intended to support the development of a *BIM academy* - currently being contemplated in Australia – tasked with developing BIM-focused learning modules for both industry and academia; and
- Based on performance assessment tools developed throughout this study – and also in collaboration with industry associations - a seed BIM accreditation and certification programme will be developed. The programme will clarify BIM performance milestones and provide individuals and organizations with incentives to assess and continuously improve their BIM performance.

11.3 Summary

Building Information Modelling (BIM) is the *current expression* of technical and procedural innovation within the construction industry. It is a methodology that generates, exchanges and manages a constructed facility's data throughout its life cycle. There are significant benefits and challenges attributed to BIM tools and workflows. To holistically understand BIM, its conceptual parts must be understood as well as the relationship between them.

Benefiting from previous research and applicable theories - and reflecting the candidate's experiential knowledge and thought experiments - this study adopted a pragmatic research design and a mixed research strategy. Through nine published papers (2007-2013), this study investigated the knowledge structures underlying the BIM domain, developed an expansive theoretical framework to represent these structures, and delivered a number of practicable tools to assist industry stakeholders to assess and improve their BIM performance.

In summary, the deliverables of this study included:

- A set of metrics and tools to assess BIM capability, maturity and competency;
- A seed competency inventory to assist in developing BIM learning modules;
- A conceptual engine to integrate BIM assessment, learning and implementation;
- An interconnected BIM dictionary to reduce topic ambiguity;
- A set of models, taxonomies and classifications to represent domain knowledge;
- A BIM ontology to formalise BIM concepts and interlink conceptual constructs;
- A visual language to simplify complex BIM topics; and
- An expandable theoretical framework to connect all deliverables – conceptual and practical - and support the development of new ones.

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PART II
SUBMITTED PAPERS

Part II aggregates all papers submitted as part of this thesis. For a discussion of paper types or contributions each paper made toward other papers and the overall study, please refer to Part I, section 9.

PAPER A1

A Proposed Framework to Investigate Building Information Modelling through Knowledge Elicitation and Visual Models

Succar, B., Sher, W., & Aranda-Mena, G. (2007). A Proposed Framework to Investigate Building Information Modelling Through Knowledge Elicitation and Visual Models. Paper presented at the Australasian Universities Building Education (AUBEA2007), Melbourne, Australia.

Download paper: http://bit.ly/BIMPaperA1

A PROPOSED FRAMEWORK TO INVESTIGATE BUILDING INFORMATION MODELLING THROUGH KNOWLEDGE ELICITATION AND VISUAL MODELS

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ABSTRACT

Building Information Modelling (BIM) is an expansive knowledge domain within the Architecture, Engineering and Construction (AEC) industry. To allow a systematic investigation of the domain, research is needed to define BIM knowledge components, connect its divergent fields and delineate its expanding boundaries. This paper introduces a research framework for identifying BIM concepts and a methodology for capturing and representing BIM interactions. It also proposes visual models to elicit expert knowledge and identifies further research requirements.

1 BUILDING INFORMATION MODELLING

Building Information Modelling (BIM) is a set of interacting policies, processes and technologies producing a "methodology to manage the essential building design and project data in digital format throughout the building's life-cycle" (Penttilä, 2006).

1.1 BIM: the term

Building Information Modelling (BIM) is an emerging technological and procedural shift within the Architecture, Engineering and Construction (AEC) industry. Researchers have been investigating the components and repercussions of building product models (Eastman, 1999) for many years before the emergence of BIM as a new term. While the mere presence of a label or an acronym is viewed by some researchers as a sign of poor lexical literacy (Santini, 2002), others refer to names as “vital for communication and useful for understanding a situation” (Bono, 1970). Many industry writers and analysts have contested the many terms available while others have argued for the acceptance of BIM *as is* because of its adoption by industry’s major CAD developers (Liaserin, 2002). Whether the term itself is useful, agreed upon or contested, BIM is continuing its proliferation in both industrial and academic circles as the ‘new CAD paradigm’ (Ibrahim, Krawczyk and Schipporeit, 2004).

1.2 Differences between terms

Some researchers have opted to differentiate between the many available terms (Lee, Wu, Aouad, Cooper and Tah, 2005) but the extensively overlapping boundaries render the uniqueness of each term questionable. From conceptual to descriptive in nature, these terms can be attributed to research or industry bodies as well as software developers. Table 1 conveys the more widely used terms in both research and industry literature while Figure 1 represents common connotations of BIM terms.

Sample Terms	**Organisation or Researcher**	**Reference**
Asset Lifecycle Information System	Fully Integrated & Automated Technology	(FIATECH, 2005)
Building Information Modelling	Autodesk and Bentley Systems	(Autodesk, 2005) (Bentley, 2006)
Building Product Models	Charles Eastman	(Eastman, 1999)
BuildingSMART™	International Alliance for Interoperability	(IAI, 2005)
nD Modelling	University of Salford – School of the Built Environment	(Lee, Wu, Marshall-Ponting, Aouad, Cooper, Koh, Fu, Betts, Kagioglou and Fischer, 2003)
Virtual Building™	Graphisoft	(Graphisoft, 2006)
Virtual Design and Construction & 4D Product Models	Stanford University– Center for Integrated Facility Engineering	(Fischer and Kunz, 2005) (Fischer, 2001)
Other terms: Integrated Model, Object Oriented Building Model, Single Building Model,…		

Table 1: terms used by researchers, institutions and organisations to describe the Building Information Model

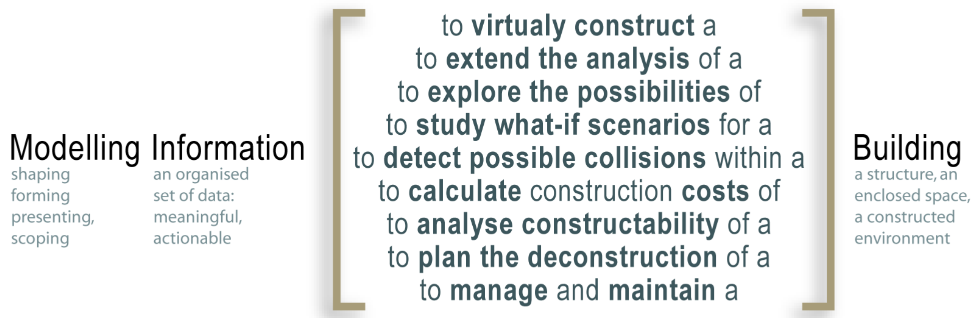

Figure 1: some of the common connotation of multiple BIM terms

Some of the underlying knowledge and computational structures represented by these terms has shifted from research circles to the industrial realm (Khemlani, 2005) while many efforts could not gain the interest of the industry (Halfawy and Froese, 2002).

1.3 The need for a framework

In many writings, seminars and workshops, BIM is argued to be a catalyst for change (Bernstein, 2005) poised to reduce industry's fragmentation (CWIC, 2004), improve its efficiency/effectiveness (Hampson and Brandon, 2004) and lower its high costs of inadequate interoperability (NIST, 2004). These assertions –abridged as they may be- include several mental constructs derived from organisational studies, information systems and regulatory fields. Such divergence and coverage highlights the *lack of* and the *necessity for* a research framework requiring systematic investigation of the BIM domain. The availability of a framework will assist in organising domain knowledge, elicit tacit expertise and facilitate the creation of new knowledge.

2 PROPOSED RESEARCH FRAMEWORK

This paper proposes a prototypical framework and an investigative methodology to identify, capture and represent BIM interactions. The framework (Table 2) is composed of three interlocking knowledge nodes (Figure 2) and their push-pull interactions (Figure 3).

2.1 The BIM Policy node

The first node is the field of interaction generating research frameworks, standards and best practices for the purpose of safeguarding benefits and minimizing conflict between BIM stakeholders

2.2 The BIM Process node

The second node is the field of interaction between construction requirements, construction deliverables, organisational structures and operational communications for the purpose of generating and maintaining building information models.

2.3 The BIM Technology node

The third node is the field of interaction between software, hardware and networking systems necessary to generate and maintain building information models.

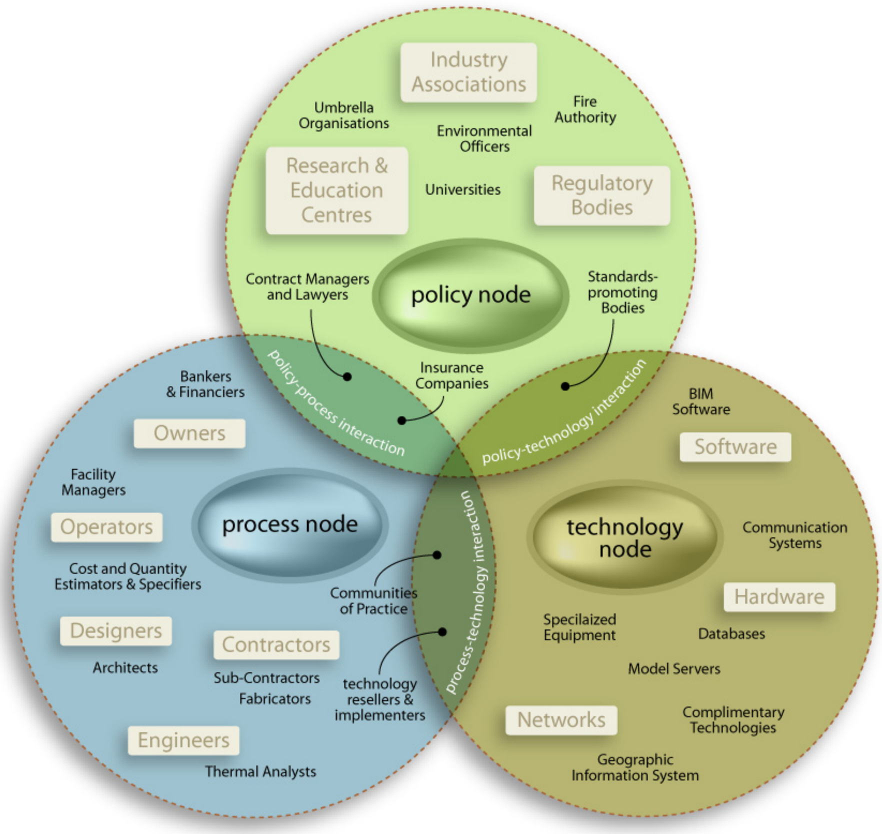

Figure 2: the proposed BIM research framework includes three interlocking knowledge nodes

		Policy node	Process node	Technology node
Definition		Policies are "written principles or rules to guide decision-making" (Clemson, 2007)	Process is "a specific ordering of work activities across time and place, with a beginning, an end, and clearly identified inputs and outputs: a structure for action" (Davenport, 1992)	Technology is "the application of scientific knowledge for practical purposes" (Oxford, 2007)
Extended node Definition		The field of interaction generating research frameworks, standards and best practices for the purpose of safeguarding benefits and minimizing contestation between BIM stakeholders	The field of interaction between construction requirements, construction deliverables, organisational structures and operational communications for the purpose of generating and maintaining the building information model (BIModel)	The field of interaction between software, hardware and networking systems necessary to generate and maintain the BIModel
Node participants		Governments, researchers, industry associations, insurance companies and regulatory bodies	Owners, operators, designers, engineers and contractors	Software, hardware and networking companies plus their development and sales channels
BIM deliverables		Policy guideline standards best practices bench marks contracts	Projects Structures	Software tools Computers & peripherals Collaborative tools
BIM Interactions	**Push**	BIM deliverables into the process node	Case studies into the policy node.	Innovative solutions into the process and policy nodes
	Pull	Information from the process node	Development of solutions from the technology node. standardisation from the policy node	Standardisation efforts from the policy node

Table 2: proposed BIM research framework

2.4 BIM interactions

BIM interactions (Figures 3) are push-pull knowledge transactions within and between BIM nodes. Push mechanisms (Holsapple and Joshi, 2006) transfer knowledge to another node or sub-node while pull mechanisms transfer knowledge to satisfy a request by another node or sub-node. Sample transactions include data transfers, team dynamics and contractual relationships between nodes and sub-nodes. The acquisition and representation of these interactions are the research deliverables of the proposed framework.

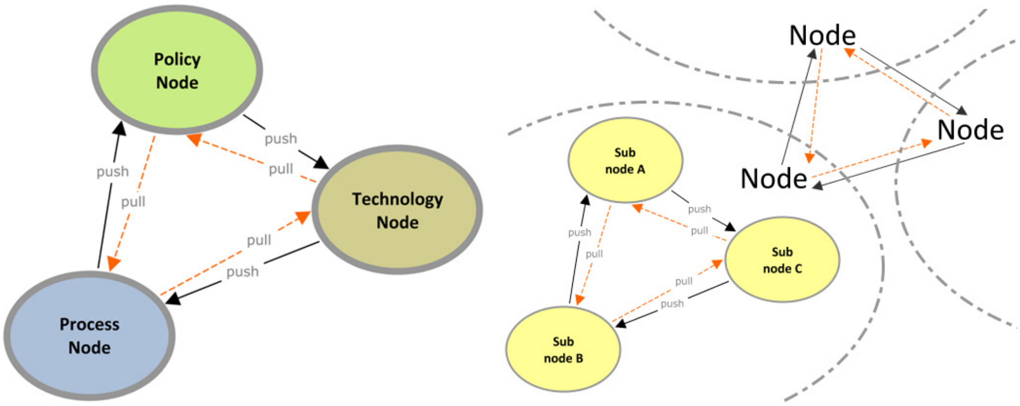

Figure 3: BIM interactions within and between framework nodes

3 CAPTURING AND REPRESENTING BIM INTERACTION

Knowledge capturing and representation activities involve the identification and acquisition of knowledge within the environment under investigation then making it available in a representation suitable for generalisation and dissemination (Holsapple and Joshi, 2006) (Holsapple and Jones, 2006).

Driven by the expanse of knowledge domains covered by the BIM research framework, the knowledge transactions are necessarily numerous and complex in nature. Such a wide and varied scope of interactions necessitates the use of visualisation to cope with the amount and complexity involved (Tergan, 2003). Representing and visualising these interactions offers a systematic way to transfer this knowledge to others (Eppler and Burkhard, 2005).

3.1 Proposed methodology to identify, capture and represent BIM interactions

This paper proposes a six-stage methodology to define, capture and represent BIM interactions through knowledge elicitation and visual knowledge models (refer to Figure 4). In the sections that follow, the first two stages are discussed and examples are provided. The remaining stages are outside the scope of this paper and are thus briefly defined.

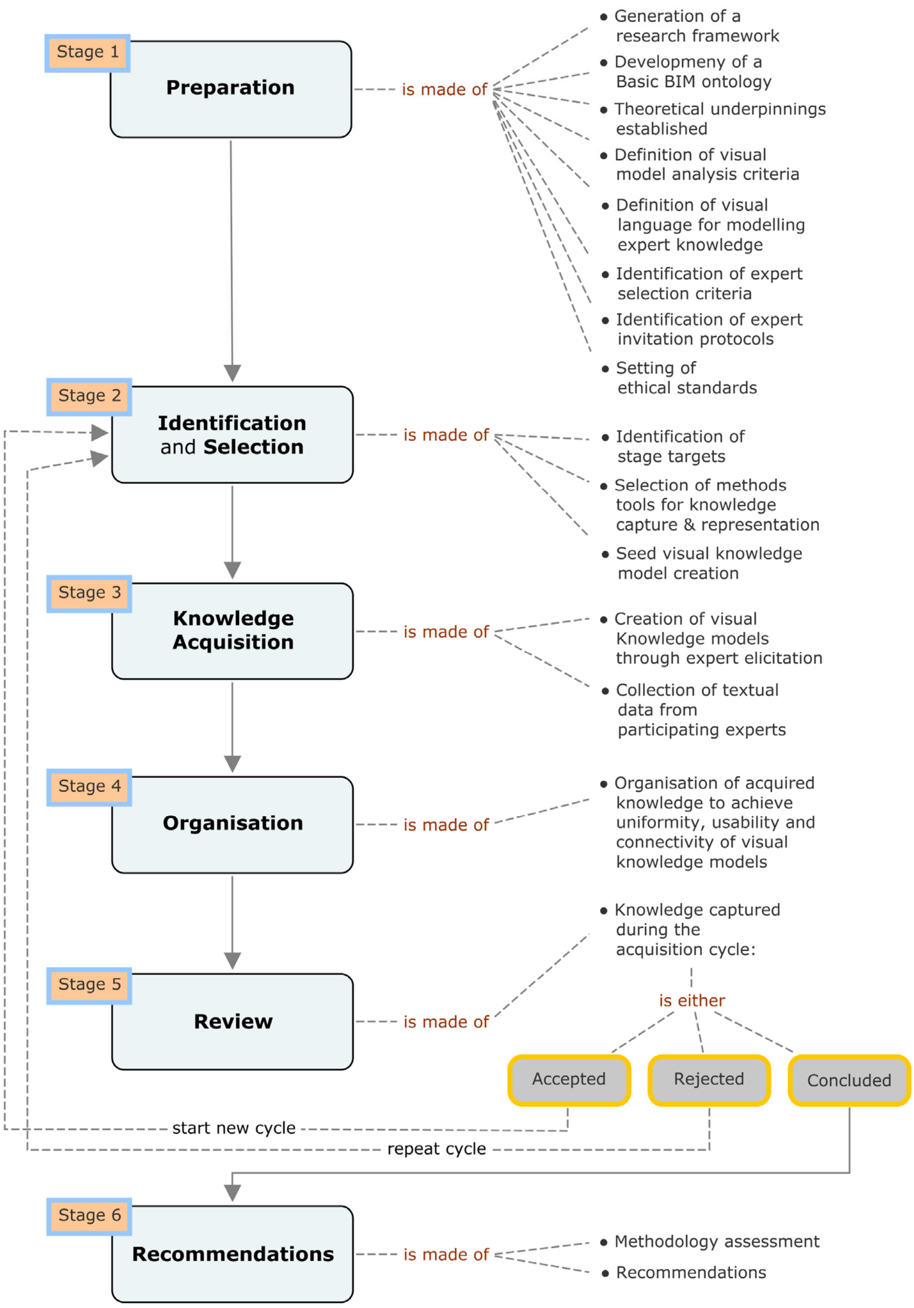

Figure 4: proposed methodology to identify, capture and represent BIM interactions

3.1.1 Stage 1: Preparation Stage

The preparation stage defines the scope of the research, generates a basic BIM ontology and discusses theoretical underpinnings, tools and research protocols.

Scope

Research scope is governed by the BIM framework introduced earlier. The framework is an attempt to organise the expanding number and complexity of BIM concepts. The framework proposes three interlocking BIM knowledge nodes and investigates the interactions within and between them.

Ontology

BIM interactions form the basis for a general BIM ontology generated through an initial seven-step approach (Noy and McGuinness, 2001). At this preparatory stage, researchers will generate a high-level formal ontology of BIM interactions and then subdivide it into lower level taxonomies and partonomies (Buchholz, 2006). The partonomies will be formalised interdependently through knowledge acquisition and representation (Stage 3) forming a facilitative basis for other acquisitions (Holsapple and Joshi, 2006) . The subdivision is intended to reduce domain complexity and allow the concurrent capture of different ontological parts.

Selection protocols

BIM interactions are complex, expansive and multi-disciplinary in nature. Capturing and representing domain knowledge necessitate the participation of both researchers and practitioners. Selection and invitation protocols of subject matter experts (SMEs) are set during this stage.

Theoretical underpinnings

The preparatory stage identifies theoretical underpinnings of knowledge capture and representation. It also defines model analysis, acceptance and rejection criteria required for the review stage.

Ethical issues

Ethical issues pertaining to expert selection and knowledge elicitation are defined.

Visual language

"Graphics is a tool that obeys universal laws that are unavoidable and undisputable but can be learned and taught"(Bertin, 1997). The preparatory stage will identify the graphical language and tools suitable to capture and visualize domain knowledge.

Definition of visualisation

Visualisation utilizes graphical means to explore, communicate or resolve logical problems (Card and Mackinlay, 1997). Visualisation can generate models in different formats (Figure 5) but share the intent to communicate and re-construct meaning (Eppler and Burkhard, 2005).

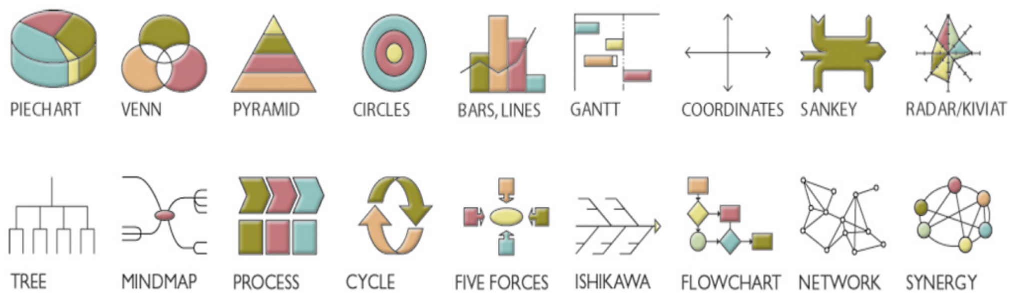

Figure 5: sample visualisation models – adopted from Eppler and Burkhard, 2005

Each model format offers a unique way to represent meaning. The VENN format (Figure 5) for example, is appropriate to represent overlapping BIM nodes while maps are better suited to capture and represent BIM interactions.

Visualisation types

Graphical representations can be subdivided into two distinct areas of research: Information Visualisation and Knowledge Visualisation (Keller and Tergan, 2005). The differences between the two visualisation approaches are summarised in Table 3 below:

<table>
<tr><th colspan="3">Information Visualisation</th><th colspan="3">Knowledge Visualisation</th></tr>
<tr><td colspan="3">Information Visualisation is the computer-assisted visual processing to gain understanding of data relations (Card and Mackinlay, 1997)</td><td colspan="3">Knowledge Visualisation focuses on knowledge discovery, representation and augmentation without being limited to computer-assisted formats (Eppler and Burkhard, 2005).</td></tr>
<tr><td colspan="3">Information visualisation has its origin in computational sciences (Keller and Tergan, 2005)</td><td colspan="3">Knowledge visualisation has it origins in social sciences (Keller and Tergan, 2005)</td></tr>
<tr><td colspan="3">Information Visualisation aims to reveal relationships between data</td><td colspan="3">Knowledge Visualisation aims to reveal relationships between information</td></tr>
<tr><td colspan="6">The semantic differences between data, information and knowledge can be summarised as follows:</td></tr>
<tr><td colspan="2">Data are observations and collectibles; data is what can be seen and collected (Landauer, 1998). Data is a raw symbol that has no meaning in itself and has no significance beyond its existence (Keller and Tergan, 2005)</td><td colspan="2">Information represents connected data whether to other data or to a context; information is what can be expressed (Landauer, 1998). Information conveys different meanings to different persons (Keller and Tergan, 2005).</td><td colspan="2">Knowledge sets a goal for information and is an expression of regularity (Landauer, 1998). Knowledge exists as part of a person, a group or a society’s cognition (Keller and Tergan, 2005).</td></tr>
</table>

Table 3: visualisation approaches and their semantic differences

Building Information Modelling includes transactions at the *data*, *information* and *knowledge* semantic levels (refer to Table 4). Representations of BIM interactions fall within the research area of knowledge visualisation; a merger between information visualisation, didactic techniques, visual cognition and visual communication (Eppler and Burkhard, 2005).

3.1.2 Stage 2: Identification and selection

This stage identifies the ontological part to be subsequently investigated in stage 3. Methods and tools best suited to conduct this investigation are selected. Stages 2, 3 and 4 are iteratively repeated to investigate other parts of the ontology within the research scope.

Identification of stage target

A target is identified for each cycle: a node, sub-node or a set of BIM interactions semantically linked within the ontology.

Selection of methods and tools

After the stage target has been identified for each cycle, methods and tools for knowledge elicitation and representation are selected.

As an example, this paper discusses map-based visualisation as a means for knowledge acquisition and representation:

Knowledge acquisition through map-based visualisation

According to Tergan (2003), map-based visualisation is a "valuable cognitive tool for supporting knowledge use in a variety of learning and instructional settings". Map-based visualisations include concept, mind and other node-link-label maps (Figure 6).

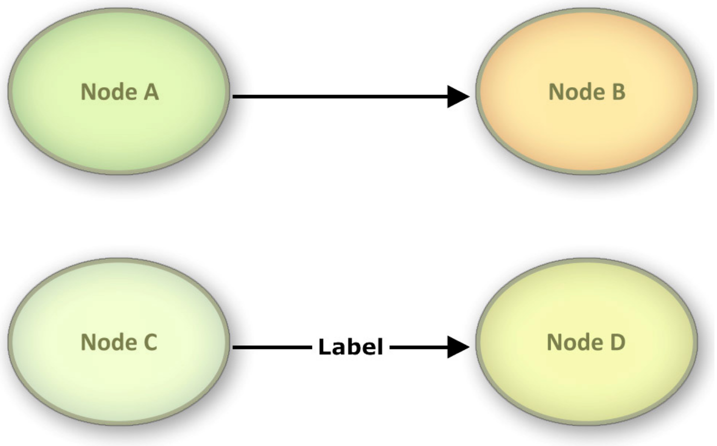

Figure 6: node-link-label maps

A summary of benefits and limitations pertaining to map-based visualisation (Tergan, 2003) (Eppler and Burkhard, 2005) are provided in Table 4:

Benefits	Risks and limitations
Assessing structural knowledge	Confusing or ambiguous visuals
Concept acquisition	Information overload
Brainstorming of ideas	Misrepresentation of concepts
Scaffolding cognitive processes in knowledge acquisition and problem solving	Oversimplification of represented concepts
Self-regulated learning	Overuse
Knowledge communication & coordination	Deliberate manipulation
Draw attention by identifying patterns	Difficult to create
Improve remembrance/recall	Difficult to maintain
Act against information overload	

Table 4: benefits and limitations of map-based visualisation

Of the many types of map-based visualisation, “concept maps made by domain experts tend to show high levels of agreement” (Hoffman and Lintern, 2006). Accordingly, this paper proposes the use of concept maps for knowledge elicitation and representation.

Using concept maps for knowledge elicitation and representation

Concept mapping, a node-link-label format, was invented in 1972 to describe explicit changes in conceptual understanding. In 1987, Concept Maps (CMaps) were first used in knowledge elicitation and as a web-based mapping application (Novak and Cañas, 2006).

Similar to cognitive maps and semantic networks (Jonassen, 2005), CMaps link concepts (nodes) together using words or phrases (labelled links) to create propositions (Figure 7).

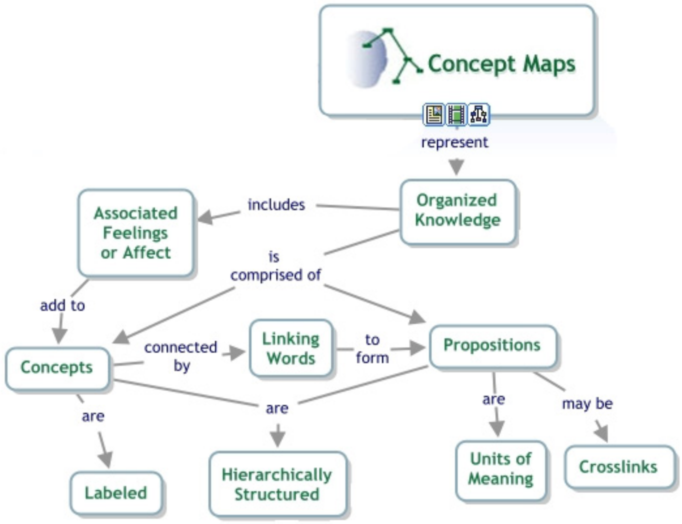

Figure 7: CMap Tools – a concept map about concept maps (Novak, 2003)

CMaps are based on explicit cognitive psychology and constructivist epistemology (Novak and Cañas, 2006). Many studies have shown CMaps’ utility in capturing knowledge and eliciting explanations (Derbentseva, Safayeni and Cañas, 2007). This paper proposes the use of concept maps as part of a methodology to elicit and represent BIM expertise.

Using a seed model

The generation of new knowledge models will depend on the critical understanding of existing models (Davenport, 1992). A seed model will be based on literature, industrial prototypes and knowledge pushed from previous cycles (example - Figure 8). It may be created at each iteration to assist in eliciting expertise and generating new models.

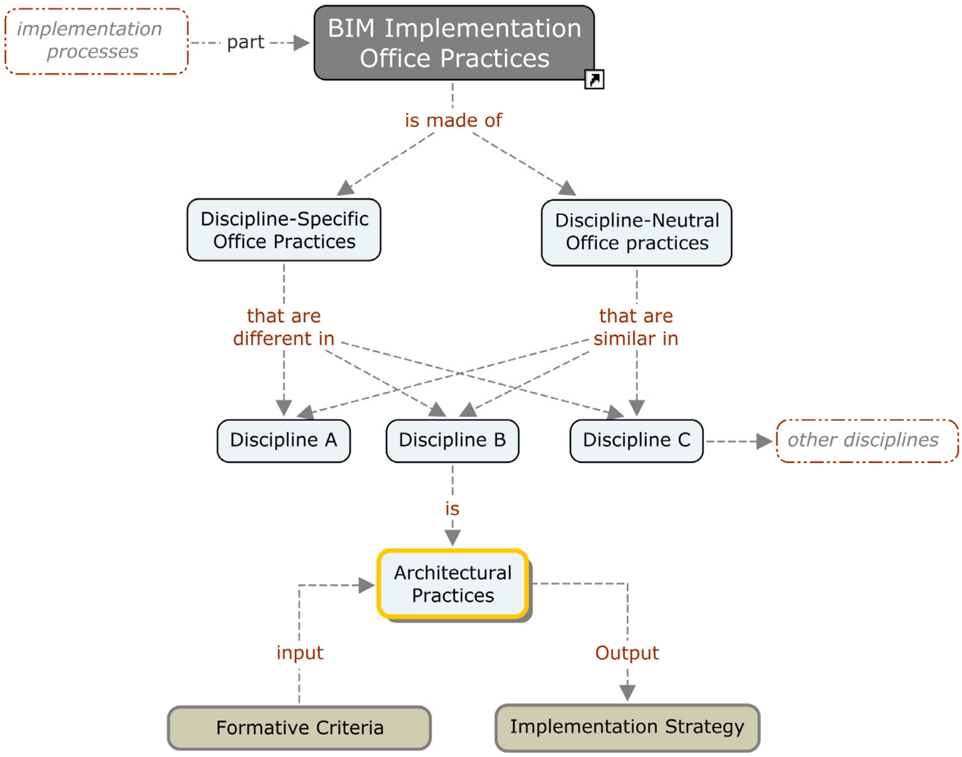

Figure 8: sample Seed model - "BIM Implementation - Office Practice"

Map-based visualisation is one method of capturing and representing expert knowledge. Other methods include jointly-authored web spaces allowing research participants to add, remove or edit content (Wikipedia, 2007).

The ontological part identified in stage 2 will drive acquisition and representation methods in stage 3.

3.1.3 Stages 3 to 6: acquisition, organisation, review and recommendations

The following stages are outside the scope of this paper and will be briefly discussed in the sections below. More research is needed to formalise the methods and tools necessary to capture and then organise knowledge in accordance with the high-level ontology and its subdivisions (identified in Stage 2).

Knowledge acquisition is a process to generate qualitative models of systems, whether social or technological. It is not the mere extraction of facts and rules from literature or experts' minds (Clancey, 1993). In Stage 3, knowledge is elicited from experts using shared visual models. Elicitation is driven by ontological identifications performed at Stage 2. Experts and researchers will jointly build knowledge models comprising explicit representations of domain interactions (Ford, Bradshaw, Adams-Webber and Agnew, 1993).

In Stage 4, the captured knowledge from each cycle is organised around the research framework then prepared for review and analysis. Uniformity, usability and connectivity of knowledge models are the main deliverables of this stage.

In Stage 5, the knowledge models are analysed to detect and then amend inconsistencies within the research framework, methodology or ontology. Subject to analysis criteria defined in Stage 1, resultant model from each research cycle will be accepted or rejected. Rejected cycles get repeated (refer to Figure 4) while accepted models get used as seed models for consequent cycles.

The investigation concludes in Stage 6 when research scope, defined in Stage 1, has been fulfilled. Resultant knowledge models are published, methodology is discussed and recommendations for further research are provided.

4 CONCLUSION

Building Information modelling is an expanding field of study incorporating many knowledge domains within the Architecture, Engineering and Construction industry. The divergence of study topics relating to BIM highlights the *lack of* and the *necessity for* a research framework allowing its systematic investigation. This paper has proposed a prototypical framework and an investigative methodology to identify, capture and represent BIM interactions. The framework is composed of three interlocking knowledge nodes: policy, process and technology. The methodology includes six stages to elicit expert knowledge through visual knowledge models within a proposed BIM ontology. Graphic representations have been surveyed and map-based visualisation has been identified as an appropriate method for knowledge elicitation. Knowledge acquisition, knowledge organisation and respective tools have been identified for further research.

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PAPER A2

Building information modelling framework: A research and delivery foundation for industry stakeholders

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Building information modelling framework: A research and delivery foundation for industry stakeholders

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ABSTRACT

Building Information Modelling (BIM) is an expansive knowledge domain within the Architecture, Engineering, Construction and Operations (AECO) industry. To allow a systematic investigation of BIM's divergent fields, its knowledge components must be defined and expanding boundaries delineated. This paper explores some of the publicly available international guidelines and introduces the BIM Framework, a research and delivery foundation for industry stakeholders. This is a 'scene-setting' paper identifying many conceptual parts (fields, stages, steps and lenses), providing examples of their application and listing some of the Framework's deliverables. This paper also identifies and deploys visual knowledge models and a specialised ontology to represent domain concepts and their relations.

1. Building Information Modelling

Building Information Modelling (BIM) is a set of interacting policies, processes and technologies generating a "methodology to manage the essential building design and project data in digital format throughout the building's life-cycle" [67]. The following sections expand on the BIM term, list related industry and academic efforts and identify the need for an investigative framework (Fig. 1).

1.1. BIM: the term

Building Information Modelling (BIM) is an emerging technological and procedural shift within the Architecture, Engineering, Construction and Operations (AECO) industry. Researchers have been investigating the components and repercussions of building product models [21] for many years before the emergence of BIM as a new term. While the mere presence of a label or an acronym is viewed by some researchers as a sign of poor lexical literacy [70], others refer to names as "vital for communication and useful for understanding a situation" [11]. Many industry writers and analysts have contested the many terms available while others have argued for the acceptance of BIM *as is* because of its adoption by industry's major CAD developers [54]. Whether the term itself is useful, agreed upon or contested, BIM is continuing its proliferation in both industrial and academic circles as the 'new CAD paradigm' [40].

1.2. Differences between terms

Some researchers have opted to differentiate between the many available terms [51] but the extensively overlapping boundaries render the uniqueness of each term questionable. From conceptual to descriptive in nature, these terms can be attributed to research or industry bodies as well as software developers. Table 1 sets out some of the more widely used terms in both research and industry literature while Fig. 2 presents some common connotations of the BIM term.

Some of the underlying knowledge and computational structures represented by these terms has shifted from research circles to the industrial realm [46] while many efforts could not attract the interest of the industry [33].

1.3. The need for a framework

In many writings, seminars and workshops, BIM is argued to be a catalyst for change [7] poised to reduce industry's fragmentation [17], improve its efficiency/effectiveness [34] and lower the high costs of inadequate interoperability [62]. These assertions — abridged as they may be — include several mental constructs derived from organisational studies, information systems and regulatory fields. Such divergence and coverage highlights the *lack of* and the *necessity for* a research framework to organise domain knowledge which, in turn, requires a systematic investigation of the BIM domain.

Additionally, the need for a systemically-defined BIM Framework extends beyond knowledge enquiry and organisation. Practitioners and educators alike will arguably find value in the delineation and

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subdivision of the BIM domain. Structured subdivisions promote understanding, dissemination and gradual implementation by presenting data and arguments in manageable sections. There is also *a need for* a framework that positions BIM as an 'integration of product and process modelling' [47] and not just as a disparate set of technologies and processes. Lastly, there is a *lack of* and a *necessity for* a framework that attempts to bridge the chasm separating 'academic' from 'industrial' understandings of BIM by providing a research and delivery structure adaptable to their complementary yet unique requirements.

1.4. Availability of other frameworks

BIM implementations and discussions continue to increase in intensity as more organisations and national bodies recognise its value-adding potential. This is evidenced by the accelerating emergence of guidelines and major reports dedicated to exploring and defining the requirements and deliverables of BIM (Table 2).

These guidelines and reports — although valuable in their own right — do not provide a foundational framework suitable for the systematic investigation of the BIM domain. The availability of a

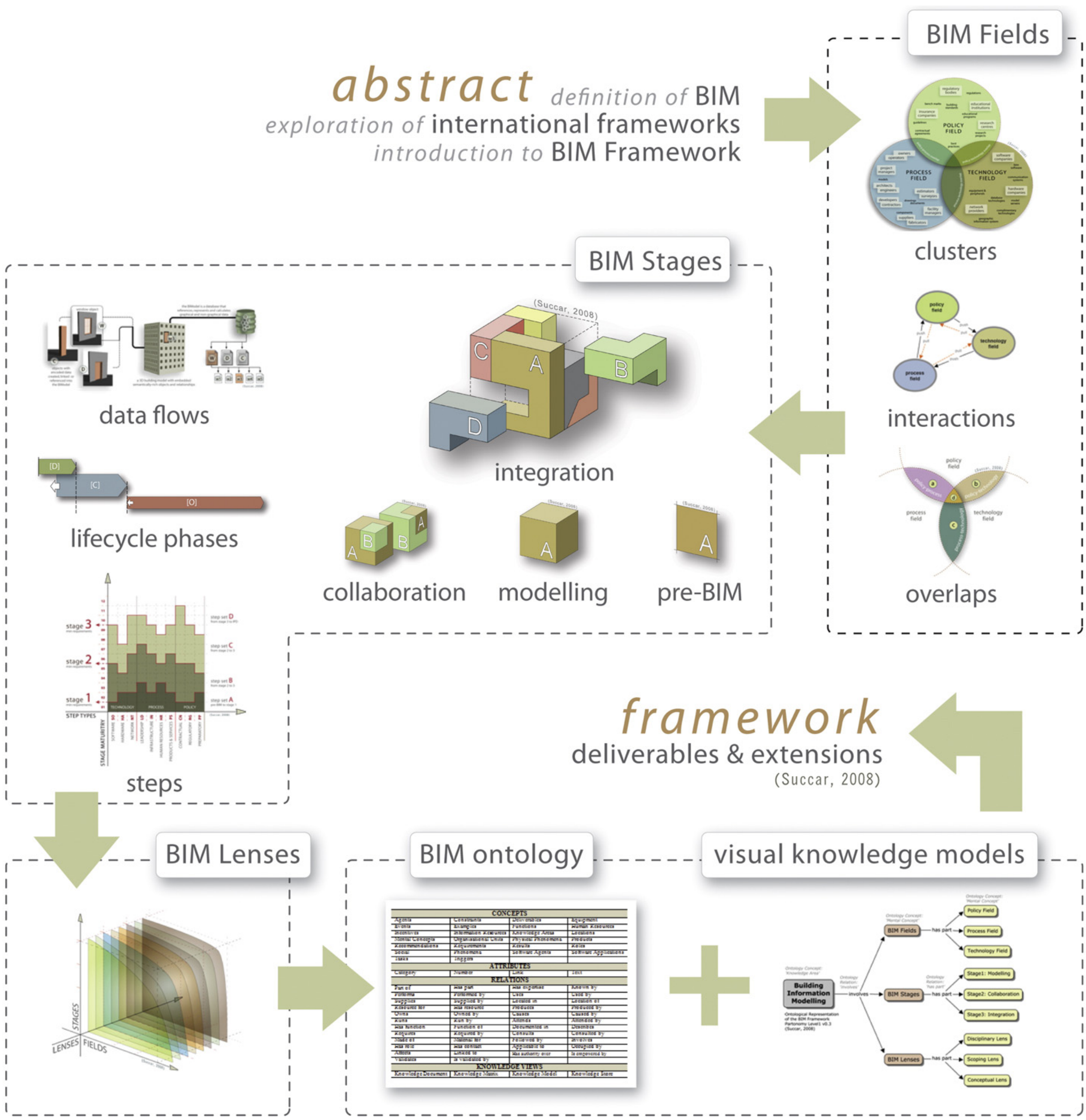


Fig. 1. Visual abstract of this paper.

Table 1
Widely used terms relating to Building Information Modelling

Sample terms	Organisation or Researcher	Reference
Asset Lifecycle Information System	Fully Integrated & Automated Technology	[24]
Building Information Modelling	Autodesk, Bentley Systems and others	[4,5]
Building Product Models	Charles Eastman	[21]
BuildingSMART™	International Alliance for Interoperability	[38]
Integrated Design Systems	International Council for Research and Innovation in Building and Construction (CIB)	[42]
Integrated Project Delivery	American Institute of Architects	[2]
nD Modelling	University of Salford — School of the Built Environment	[52]
Virtual Building™	Graphisoft	[29]
Virtual Design and Construction & 4D Product Models	Stanford University— Centre for Integrated Facility Engineering	[26,25]

Other terms: Integrated Model, Object Oriented Building Model, Single Building Model etc.

framework will assist in organising domain knowledge, elicit tacit expertise and facilitate the creation of new knowledge. The utility of such frameworks is ably articulated by Minsky (1975) who states: "Here is the essence of the theory: When one encounters a new situation (or makes a substantial change in one's view of the present problem) one selects from memory a structure called a Frame. This is a remembered framework to be adapted to fit reality by changing details as necessary. A frame is a data-structure for representing a stereotyped situation…Attached to each frame are several kinds of information. Some of this information is about how to use the frame. Some is about what one can expect to happen next. Some is about what to do if these expectations are not confirmed. We can think of a frame as a network of nodes and relations." [60]

2. BIM Framework: an introduction

This section introduces the BIM Framework, a research and delivery foundation that maps domain dynamics and allows AECO stakeholders to understand underlying knowledge structures and negotiate BIM implementation requirements.

The framework is multi-dimensional and can be represented by a tri-axial knowledge model (Fig. 3) comprising of:

- BIM Fields of activity identifying domain 'players' and their 'deliverables'. These fields are represented on the *x*-axis.
- BIM Stages delineating implementation maturity levels (*y*-axis)
- BIM Lenses providing the depth and breadth of enquiry necessary to identify, assess and qualify BIM Fields and BIM Stages (*z*-axis)

2.1. BIM Fields

This section identifies three interlocking BIM Fields of activity (Fig. 4): Technology, Process and Policy (TPP) with two sub-fields each: players and deliverables. An introduction to the three BIM Fields is provided below followed by Field Interactions and Field Overlaps.

2.1.1. The BIM Technology Field

Technology is "the application of scientific knowledge for practical purposes" [65]. The Technology Field clusters a group of players who specialises in developing software, hardware, equipment and networking systems necessary to increase efficiency, productivity and profitability of AECO sectors. These include organisations which generate software solutions and equipment of direct and indirect applicability to the design, construction and operation of facilities.

2.1.2. The BIM Process Field

Process is "a specific ordering of work activities across time and place, with a beginning, an end, and clearly identified inputs and outputs: a structure for action" [18]. The Process Field clusters a group of players who procure, design, construct, manufacture, use, manage and maintain structures. These include facility owners, architects, engineers, contractors, facility managers and all other AECO industry players involved in the ownership, delivery and operations of buildings or structures.

2.1.3. The BIM Policy Field

Policies are "written principles or rules to guide decision-making" [13]. The Policy Field clusters a group of players focused on preparing practitioners, delivering research, distributing benefits, allocating risks and minimising conflicts within the AECO industry. These players do not generate any construction products but are specialised organisations — like insurance companies, research centres, educational institutions and regulatory bodies — which play a pivotal preparatory, regulatory and contractual roles in the design, construction and operations process.

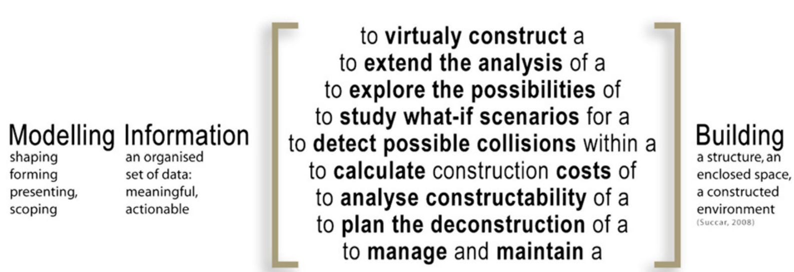


Fig. 2. Some common connotations of multiple BIM terms.

Table 2
A non-exhaustive list of publicly-available guides, reports and visions relating to BIM

Origin	Organisation	Project	Type and date	Description	Ref and link
Australia	CRC-CI	National Guidelines & Case Studies	Guidelines and six case studies — 2008.	"The guidelines will highlight open and consistent processes and test selected softwares compatibility"	[16] 5h95p5
Denmark	BIPS	Digital Construction	Guidelines 2007 in 4 parts (251+ pages)	A guide made of 4 components: 3D CAD Manual, 3D Working Method, Project Agreement and Layer — and Object Structures	[9] bipsBIM
Finland	SENATE Properties	BIM Requirements 2007	Guidelines — 2007 in 9 volumes (200 pages) subdivided by discipline	General operational procedures in BIM projects and detailed general requirements of BIModels — focuses on the design phase	[71] 63btnq
Netherlands	TNO	E-BOUW	Framework —2008 presented through a wiki	"a BIM Framework consisting of seventeen orthogonal Dimensions that describe in general the Building Information Modelling world constituting a "Way of Thinking" about BIM	[20] tnowiki
Norway	STATSBYGG	HITOS	Documented Pilot (52 pages). sections based on modelling roles	A 'full-scale IFC test' documenting experiences gained on a collaborative project	[50] 62kmd3
United States	AGC	Contractor's Guide to BIM	Guidelines — version 1, September 2006 (48 pages)	"This guide is intended to help contractors understand how to get started (with BIM or VDC)	[1] 695hjq
	AIA	Integrated project Delivery (IPD)	Guide — 2007 (62 pages)	"A project delivery approach that integrates people, systems, business structures and practices into a process that collaboratively harnesses the talents and insights of all participants to optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication & construction"	[2] 6kadgh
	GSA	3D–4D-BIM Program	Guidelines —2006 in 7 series	A guide "intended for GSA associates and consultants engaging in BIM practices for the design of new construction and major modernization projects for GSA"	[32] GSABIM
	NIST	NBIMS National Building Information Modelling Standards	Guidelines — 2007 (183 pages)	"NBIMS establishes standard definitions for building information exchanges to support critical business contexts using standard semantics and ontologies…(to be)..implemented in software"	[63] NBIMSpdf
	USACE	US Army Corps of Engineers	BIM — A roadmap for Implementing BIM to solve the Time and Cost Challenges of MILCON Transformation (96 pages)	"The scope of this plan is to focus on the implementation of BIM in the U.S. Army Corps of Engineer's civil works and military construction business processes, including the process for working with the USACE Architectural Engineering Construction (AEC) industry partners and software vendors"	[77] 6qzpe9
	USCG	U.S. Coast Guard	BIM User Guides and Standards (partial publicly-available information)	"The aim is to develop and maintain a BIM standard"	[78]
European	Consortium of organisations	InPro	Report — 2006 till 2010 (131 pages in 4 or more parts so far)	"The Open Information Environment is a set of results due to the junction of two approaches: on one hand business processes and the required organisation and on the other hand the underlying technologies supporting the business processes."	[68] 5ref9c
	Consortium of organisations	CONCUR Concurrent Engineering in Building and Civil Engineering	Demonstration Project — 2002	"CONCUR has demonstrated concurrent working in construction engineering and design between project partners using advanced web based ICT"	[14] 6pst5l
	Consortium of organisations	ERABUID	Report — 2008	Review of the development and implementation of BIM: technology, standards and necessary future steps	[48] Erabuild
	Consortium of organisations	STAND-INN	Development Process — Quick Guide 2007	"Integration of performance based building standards into business processes (and manufacturing processes) using IFC standards to enhance innovation and sustainable development"	[72] STAND-INN

Note 1: It's worth mentioning that the efforts of the International Alliance for Interoperability (http://tinyurl.com/iai-int) are a basis for many guidelines and reports listed above.
Note 2: For web addresses, please add http://tinyurl.com/ in front of the code. Example (http://tinyurl.com/2sjlg9).

2.1.4. BIM Interactions

BIM Interactions are push–pull knowledge transactions occurring within or between fields and sub-fields (Fig. 5). Push mechanisms [37] transfer knowledge to another field or sub-field while pull mechanisms transfer knowledge to satisfy a request by another field or sub-field. Sample transactions include data transfers, team dynamics and contractual relationships between fields and sub-fields. The identification and representation of these interactions are an important component of the Framework's deliverables.

Table 3 below summarises the three BIM Fields, lists their players and deliverables and identifies some of their interactions.

2.1.5. BIM field overlaps

The three fields overlap as they share players and deliverables (see Fig. 6). This overlap between fields occurs when:

(1) A deliverable requires players from two or more fields. The development and application of non-proprietary interoperable schemas (IFCs for example) require the joint efforts of Policy players (researchers and policy makers) as well as Technology players (software developers).

(2) Players pertaining to one field generate deliverables classified in another. For example, the Australian Institute of Architects is an 'industry body' whose members are Process players

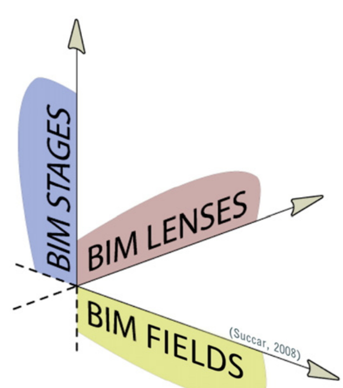


Fig. 3. BIM Framework: Fields, Stages and Lenses — tri-axial model.

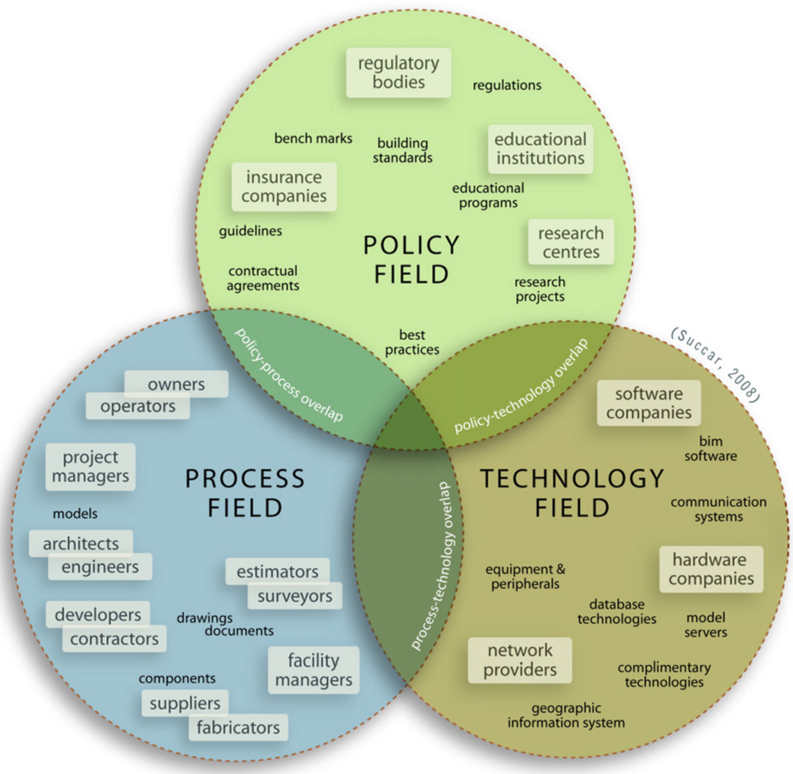


Fig. 4. Three interlocking Fields of BIM activity — venn diagram.

(architects) generating Policy deliverables (guidelines and best practices) rather than Process deliverables (building designs and construction details).

2.2. BIM maturity stages

There are voluminous possibilities attributed to BIM representing an array of challenges which need to be addressed by Architecture, Engineering, Construction and Operations (AECO) stakeholders. Having identified the BIM Fields, this section identifies the multiple stages which delineate implementation maturity levels.

BIM Stages — the second 'dimension' of the proposed framework — identifies a fixed starting point (the status before BIM implementation), three fixed BIM maturity stages and a variable ending point which allows for unforseen future advancements in technology. This paper uses the term Pre-BIM to represent industry status prior to BIM

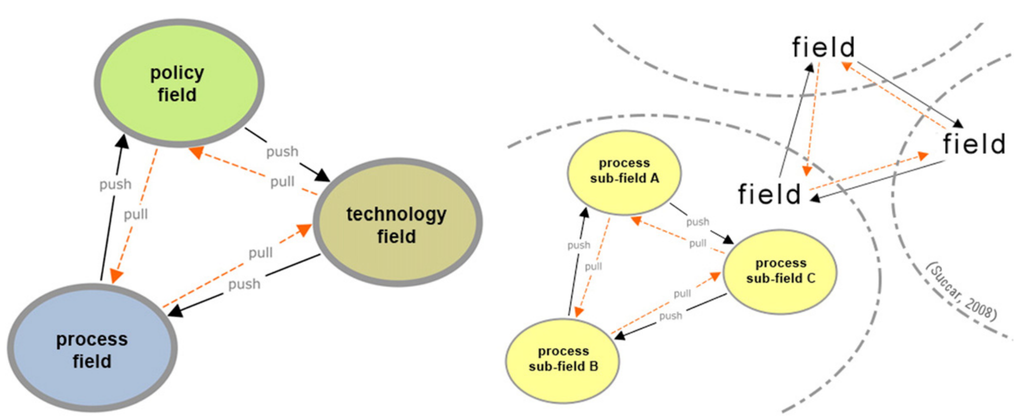


Fig. 5. BIM Interactions between and within Fields — combined view.

Table 3
BIM Fields — players, deliverables and interactions

		Policy Field	Process Field	Technology Field
Definition		Policies are "written principles or rules to guide decision-making" [13]	Process is "a specific ordering of work activities across time and place, with a beginning, an end, and clearly identified inputs and outputs: a structure for action" [18]	Technology is "the application of scientific knowledge for practical purposes" [65]
Extended Field Definition		The field of interaction generating research, talents, standards and best practices for the purpose of safeguarding benefits and minimizing contestation between AECO stakeholders	The field of interaction between design, construction and operational requirements for the purpose of generating and maintaining structures and facilities	The field of interaction between software, hardware, equipment and networking systems for the purpose of enabling or supporting the design, construction and operations of structures and facilities
Players (sub-field)		Governments, researchers, educational institutions insurance companies and regulatory bodies, …	Owners, operators, architects, engineers, estimators, surveyors, developers, contractors, sub-contractors suppliers, fabricators, facility managers, …	Software, hardware, network and equipment companies plus their development and sales channels
Deliverables (sub-field)		Regulations, guidelines, standards, best practices, bench marks, contractual agreements, educational programmes	Construction products and services including drawings, documents, virtual models/components, physical components, structures and facilities	Software, hardware, peripherals, network solutions, and office/ site equipments
Sample interactions between fields and sub-fields	Push into other fields	– Skilled graduates, standards, guidance into Process – Concepts, mathematical solutions into Technology	– Case studies into Policy – Feedback to Technology	Innovative solutions and new equipment into Policy and Process
	Pull from other fields	– Subject matter experts from Process – Interoperability from Technology	– Development of solutions from Technology – Standards, guidelines and graduates from Policy	– Standardisation efforts from Policy – Requirements and experiences from Process
	Push–pull within the same field	Interchanges between research, education and accreditation boards	Architect's Instructions (AI-push) and Request Further Information (RFI-pull)	Hardware capabilities (push) and software requirements (pull)

implementation and Integrated Project Delivery (IPD) to denote an *approach to* or an *ultimate goal of* implementing BIM [2].

The BIM Framework identifies BIM maturity within organisations, projects and industry as a series of stages which stakeholders need to implement gradually and consecutively. Each of these stages is further subdivided into steps. What separates stages from steps is that stages are *transformational* or *radical* changes while steps are *incremental* [35,75]. BIM maturity includes TPP (technology, process

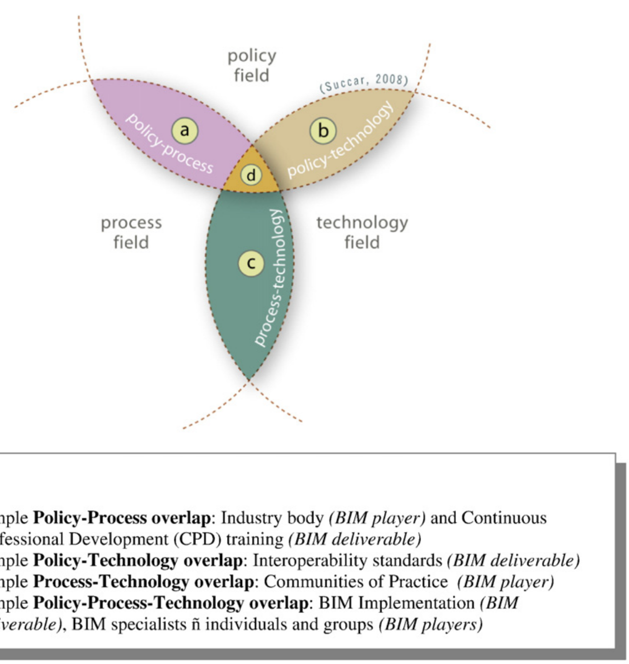


Fig. 6. BIM Fields' overlapping players and deliverables — fan model.

Fig. 7. BIM maturity is subdivided into three stages — linear view.

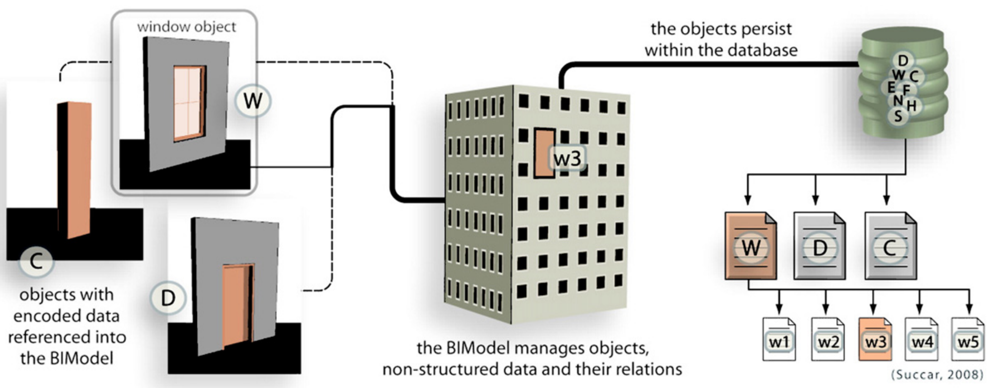


Fig. 8. Building Information Models and their objects — flow diagram.

and policy) components and is subdivided into three stages (Fig. 7) which are:

- BIM Stage 1: object-based modelling
- BIM Stage 2: model-based collaboration
- BIM Stage 3: network-based integration

Without overwhelming this paper with all variables the Framework measures BIM Stages against, it is important to introduce at least two of them: BIM Data Flows and Project Lifecycle Phases.

2.2.1. BIM Data Flows

Building Information Models are made of 'smart' objects [39] which represent physical elements like doors and columns [26] and encapsulate 'intelligence' [33] (refer to Fig. 8). An AECO smart object is different to a CAD entity that holds little or no meta-data [39]. Object intelligence, also referred to as 'semantic richness' [33] and data flows between BIM stakeholders are both critical and detectable variables of BIM maturity.

BIM data flows are varied and include the transfer of structured/computable (ex: databases), semi-structured (ex: spreadsheets) or non-structured/non-computable data (ex: images) between computer systems [49,33]. This transfer may be file-based or through data push–pull between servers and client machines [28]. As such, BIM data flows do not only include sending and receiving 'semantically rich' objects — the main components of BIModels — but also the sending and receiving of document-based information [27].

This variety in data and its methods of transfer between BIM players may be classified and later measured against BIM maturity stages in a multitude of ways. The author will however identify only one 'umbrella' classification suited for the purposes of this paper. BIM data flows can either be BIM data 'exchanges' or BIM data 'interchanges':

- A BIM data *exchange* is when a BIM player exports or imports data that is neither structured nor computable. A typical example of data exchange is the export of 2D CAD drawings out of 3D object-based models resulting in significant loss of geometric and semantic data.
- A BIM data *interchange* is when a BIM player exports and imports data that is structured and computable by another application. Interchanges assume 'adequate interoperability' between the sender and the receiver systems — Interoperability is defined as "the ability of two or more systems or components to exchange information and to use the information that has been exchanged" [41]. BIM interchange — an interoperable exchange of BIM data — may occur in many technical ways including the exchange of proprietary (ex: RVT and DGN), open-proprietary[1] (like DWF and many eXtensible Markup Languages) or non-proprietary file formats (ex: IFC and CIS/2). A typical example of 'adequate interoperability' is the export of a CIS/2 file from one BIM application and its subsequent import by another without major loss of object data richness.

2.2.2. Project Lifecycle Phases

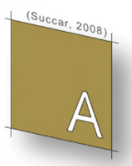
Construction projects pass through three major lifecycle phases: Design [D], Construction [C] and Operations [O]. The Framework subdivides these phases into sub-phases (Table 4) which are in turn further subdivided into multiple activities, sub-activities and tasks (Fig. 9). Example: [D] Design Phase, [D1] Architectural, Structural and Systems Design, [D1.1] Architectural Design, [D1.1a] Conceptualisation, [D1.1a.01] 3D Modelling.

BIM implementation will arguably change the *components of* and *relations between* lifecycle phases, activities and tasks; changes caused by varying BIM Interactions (refer back to Section 2.1.2) and BIM Maturity. The next few sections will include a hypothetical

[1] For more information on proprietary/open-proprietary, please refer to http://www.openformats.org/en1.

representation of the effects of BIM Maturity on lifecycle phase duration, phase overlap and model semantic richness. First, a synopsis of pre-BIM — industry status prior to BIM implementation:

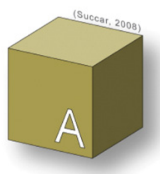
2.2.3. Pre-BIM Status synopsis[2].



The construction industry is characterised by adversarial relationships where contractual arrangements encourage risk avoidance and risk shedding. Much dependence is placed on 2D documentation to describe a 3D reality. Even when some 3D visualisations are generated, these are often disjointed and reliant on two-dimensional documentation and detailing. Quantities, cost estimates and specifications are generally neither derived from the visualisation model nor linked to documentation.

Similarly, collaborative practices between stakeholders are not prioritised and workflow is linear and asynchronous. Under pre-BIM conditions, industry suffers from low investment in technology and lack of interoperability [17,62].

2.2.4. BIM Stage 1: object-based modelling synopsis[3]



BIM implementation is initiated through the deployment of an 'object-based 3D parametric software tool' similar to ArchiCAD®, Revit®, Digital Project® and Tekla®. At Stage 1, users generate single-disciplinary models within either design [D], construction [C] or operation [O] — the three Project Lifecycle Phases. BIModelling deliverables include architectural design models [D] and duct fabrication models [C] used primarily to automate generation and coordination of 2D documentation and 3D visualisation. Other deliverables include basic data exports (ex: door schedules, concrete quantities, FFE costs,…) and light-weight 3D models (ex: 3D DWF, 3D PDF, NWD, etc…) which have no modifiable parametric attributes.

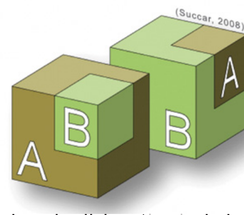
Collaborative practices at Stage 1 are similar to pre-BIM Status and there are no significant model-based interchanges between different disciplines. Data exchanges between project stakeholders are unidirectional and communications continue to be asynchronous and disjointed. As only minor process changes occur at Stage 1, pre-BIM contractual relations, risk allocations and organisational behaviour persist. However, the semantic nature of object-based models and their 'hunger' for early and detailed resolution of design and construction matters encourage 'fast-tracking' of Project Lifecycle Phases (Fig. 10).

The Knowledge Model above hypothesizes how object-based modelling encourages fast-tracking — when a project is still executed in a phased manner yet design and construction activities are overlapped to save time [43]. The author argues that, after achieving maturity within Stage 1 implementations, BIM players will acknowledge the potential benefits of engaging other design and construction players with similar modelling capabilities. Such acknowledgement and subsequent action will lead these players to another revolutionary TPP change: model-based collaboration.

Table 4
Project Lifecycle Phases and sub-phases

Design phase		Construction phase		Operations phase	
D1	Conceptualisation, programming and cost planning	C1	Construction planning and construction detailing	O1	Occupancy and operations
D2	Architectural, structural and systems design	C2	Construction, manufacturing and procurement	O2	Asset management and facility maintenance
D3	Analysis, detailing, coordination and specification	C3	Commissioning, as-built and handover	O3	Decommissioning and major re-programming

2.2.5. BIM Stage 2: Model-Based Collaboration synopsis[4]



Having developed single-disciplinary modelling expertise in Stage 1 implementations, Stage 2 players actively collaborate with other disciplinary players. This may occur in many technological ways following each player's selection of BIM software tools. Two different examples of model-based collaboration include the interchange (interoperable exchange) of models or part-models through 'proprietary' formats (ex: between Revit® Architecture and Revit® Structure through the .RVT file format) and non-proprietary formats (ex: between ArchiCAD® and Tekla® using the IFC file format).

Model-based collaboration can occur *within one* or *between two* Project Lifecycle Phases. Examples of this include the Design–Design interchange of architectural and structural models [DD], the Design–Construction interchange of structural and steel models [DC] and the Design–Operations interchange of architectural and facility maintenance models [DO]. It is important to note that *only one* collaborating model needs to hold 3D geometric data to allow for semantic interchange between two disciplines. An example of this is the [DC] interchange between a 3D object-based model (ex: Digital Project®), scheduling database (ex: Primavera® or MS project®) or a cost estimating database (ex: Rawlinsons or Timberline®). Such interchanges allow the generation of 4D (time analysis) and 5D (cost estimating) studies respectively.

Although communications between BIM players continue to be asynchronous, pre-BIM demarcation lines separating roles, disciplines and lifecycle phases start to fade. Some contractual amendments become necessary[5] as model-based interchanges augment and start replacing document-based workflows. Stage 2 maturity also alters the granularity of modelling performed at each lifecycle phase as higher-detail construction models move forward and replace (partially or fully) lower-detail design models (Fig. 11).

The Knowledge Model above hypothesizes how model-based collaboration is a factor in instigating fast-tracking and changing relative modelling intensity within each lifecycle phase. The author argues that the overlap depicted is driven by construction players increasingly providing design-related services as part of their Stage 2 offerings and design players increasingly adding construction and procurement information into their design models. Also, changes in semantic richness across lifecycle phases occur as detailed

[2] The graphical symbol used above represents 2D hand-drawn, 2D computer-aided drafting or 3D non-object based software technologies similar to AutoCAD®, SketchUP® and the like.
[3] The graphical symbol used above represents a single-disciplinary 3D model exemplified by an architect's ArchiCAD®, a structural engineer's Revit® or a steel detailer's Tekla® model.
[4] The graphical symbol used above represents the interchange of 3D models between two different disciplines. This can be exemplified by two-way linking of Revit® Architectural and Structural models (a proprietary interoperable exchange) or the interchange of IFC- files exported out of multi-disciplinary BIM applications (a non-proprietary interoperable exchange).
[5] Refer to IPD Guide and ConsensusDOCS 301: BIM Addendum.

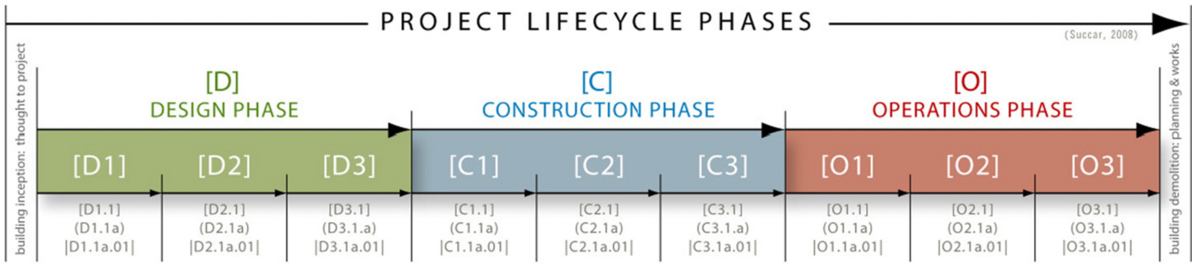
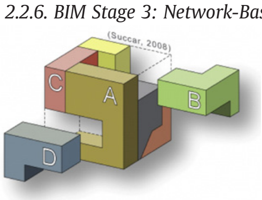


Fig. 9. Phases, sub-phases, activities, sub-activities and tasks — linear visual model.

construction and fabrication models (ex: steel detailing and duct fabrication models) partially replace the more generic upstream structural and mechanical design models.

2.2.6. BIM Stage 3: Network-Based Integration synopsis[6]



In this stage semantically-rich integrated models are created, shared and maintained collaboratively across Project Lifecycle Phases. This integration can be achieved through model server technologies (using proprietary, open or non-proprietary formats), single integrated/distributed federated databases [6,53] and/or SaaS (Software as a Service) solutions [81].

BIM Stage 3 models become interdisciplinary nD models [52] allowing complex analyses at early stages of virtual design and construction. At this Stage, model deliverables extend beyond semantic object properties to include business intelligence, lean construction principles, green policies and whole lifecycle costing. Collaborative work now 'spirals iteratively' around an extensive, unified and sharable data model [22].

From a process perspective, synchronous interchange of model and document-based data cause Project Lifecycle Phases to overlap extensively forming a phase-less process (Fig. 12).

The Knowledge Model above hypothesizes how network-based integration causes 'concurrent construction' — a term used when "all project activities are integrated and all aspects of design, construction, and operation are concurrently planned to maximize the value of objective functions while optimizing constructability, operability and safety" [43].

BIM Stage 3 implementations necessitates major reconsideration of contractual relationships, risk-allocation models and procedural flows. The prerequisite for all these changes is the maturity of network/software technologies allowing a shared interdisciplinary model to provide two-way access to project stakeholders. The maturity of all these technologies, processes and policies will eventually facilitate an Integrated Project Delivery.

2.2.7. Integrated Project Delivery synopsis

Integrated Project Delivery, a term popularised by the American Institute of Architects California Council [2] is, in the author's view, suitable for representing the long-term vision of BIM as an amalgamation of domain technologies, processes and policies. The term is generic enough and potentially more readily understandable by industry than "Fully Integrated and Automated Technology" [24] or "nD Modelling" [52] as two prominent examples.

The selection of Integrated Project Delivery (IPD) as the 'goal' of BIM implementations is not to the exclusion of other visions appearing under different names. On the contrary, the path from Pre-BIM (a fixed starting point), passing through three well defined Maturity Stages towards a loosely defined IPD is an attempt to include all pertinent BIM visions irrespective of their originating sources; some of these visions are quoted below:

- The "Integrated Project Delivery (IPD) is a project delivery approach that integrates people, systems, business structures and practices into a process that collaboratively harnesses the talents and insights of all participants to optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction. IPD principles can be applied to a variety of contractual arrangements and IPD teams can include members well beyond the basic triad of owner, architect, and contractor. In all cases, integrated projects are uniquely distinguished by highly effective collaboration among the owner, the prime designer, and the prime constructor, commencing at early design and continuing through to project handover."[2]
- The Integrated Design Solutions "are improved collaboration, coordination, communication, decision support, and other work processes enabled by increased horizontal, vertical, and temporal integration of data and information management to enhance the value added in whole network of shareholders throughout the building lifecycle."[42]
- An nD model is an extension of the building information model by incorporating all the design information required at each stage of the lifecycle of a building facility [52,51]. nD "is the parallel utilisation of building information for different analyses and evaluations …that will enable all stakeholders to experience the building, not just in a visual environment but in an information rich interactive system of all senses including acoustic (for ambient sound etc) and smell (to stimulate polluted environments)' etc. nD modelling '… is a new approach orientated to integrate existing and non-existing modelling approaches into a new way to deal with the different dimensions of a project from a predictive perspective."[52]
- FIATECH's vision is of "fully integrated and highly automated project processes coupled with radically advanced technologies across all phases and functions of the project/facility lifecycle".[24]

2.2.8. Introduction to BIM Steps

The volume and complexity of changes identified in BIM Stages — at both organisational and industrial levels — are transformational

[6] The graphical symbol used above represents the integration of 3D models using a network-based technology. Each of the single-disciplinary models is an integral part of the resulting inter-disciplinary model.

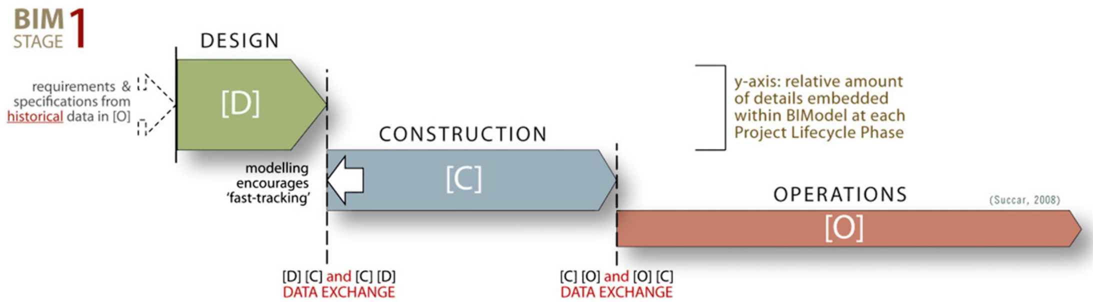


Fig. 10. Project Lifecycle Phases at BIM Stage 1 — linear model.

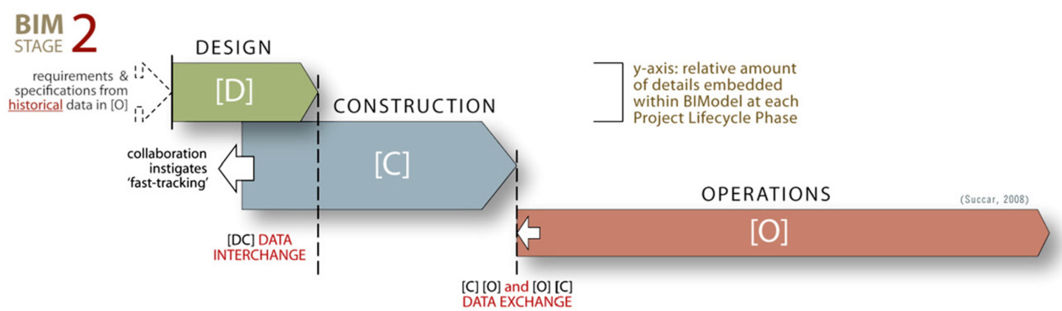


Fig. 11. Project Lifecycle Phases at BIM Stage 2 — linear model.

and cannot be implemented without traversing incremental evolutionary steps. The sections below identify BIM Steps which populate the passage from Pre-BIM to BIM Stage 1, through each of the three Stages and towards Integrated Project Delivery. Each step can either be a *prerequisite for* reaching a stage or a *maturity level within* each Stage.

2.2.8.1. Different Step Sets. The collection of steps required when working towards or within a BIM Stage — across the continuum from pre-BIM to IPD — is driven by different *perquisites for, challenges within* and *deliverables of* each BIM Stage. Steps can be identified in accordance with their location on the continuum (Fig. 13):

- A Steps: from pre-BIM Status leading to BIM Stage 1
- B Steps: from BIM Stage 1 maturing towards BIM Stage 2
- C Steps from BIM Stage 2 maturing towards BIM Stage 3
- D Steps are maturity levels within Stage 3 leading to Integrated Project Delivery

2.2.8.2. BIM Steps in relation to Fields. This paper has identified three BIM Fields: Technology, Process and Policy. The BIM Framework makes use of these subdivisions to distinguish between three types of steps *leading to* or *transitioning between* BIM stages (Fig. 14):

- Technology Steps in *software, hardware* and *networks*. For example, the availability of a BIM tool allows the migration from drafting-based to object-based workflow (BIM Stage 1)
- Process Steps in *Leadership, Infrastructure, Human Resources* and *Products/Services*. For example, collaboration processes and database-sharing skills are necessary to allow model-based collaboration (BIM Stage 2).
- Policy Steps in *contracts, regulations* and *research/education*. For example, alliance-based and risk-sharing contractual agreements are pre-requisites to achieving integrated practices (BIM Stage 3).

Fig. 15 below identifies some of these BIM Step types in an indicative and non-exhaustive manner.

2.2.8.3. BIM Steps matrix. BIM Steps act as *prerequisites of* or *maturity levels within* BIM Stages. Steps will assist BIM implementation efforts by identifying activities, services and products necessary to fulfil Stage requirements. Representing these visually will also aid in assessing organisations' maturity levels, what steps have been accomplished or are still required. Fig. 16 is a generic 'knowledge visualisation' (refer to Section 4) of BIM steps while Fig. 17 is a hypothetical view of an organisation's BIM implementation efforts seen through the matrix.

It is important to note that BIM Steps, their number, delineation and maturity will be analysed against relevant maturity models including CMMI®[7], P-CMM®[8], ISO/IEC 15504[9], and BIM_CMM[10] in future publications. An introduction to maturity models or an elaboration on concepts like 'key' and 'non-key steps' cannot be succinctly introduced in this 'scene-setting' paper.

2.3. BIM Lenses

BIM Lenses represent the third dimension of the Framework and generate its depth of enquiry. BIM Lenses are distinctive layers

[7] Capability Maturity Model Integration, refer to http://www.sei.cmu.edu/cmmi/index.html.

[8] People Capability Maturity Model, refer to http://www.sei.cmu.edu/cmm-p/version2/index.html.

[9] ISO/IEC 15504-4:2004 Information technology - Process assessment - Part 4: Guidance on use for process improvement and process capability determination, refer to http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=37462.

[10] The National BIM Standard Capability Maturity Model – BIM Capability Maturity Model, tool can be downloaded from http://www.facilityinformationcouncil.org/bim/pdfs/BIM_CMM_v1.8.xls.

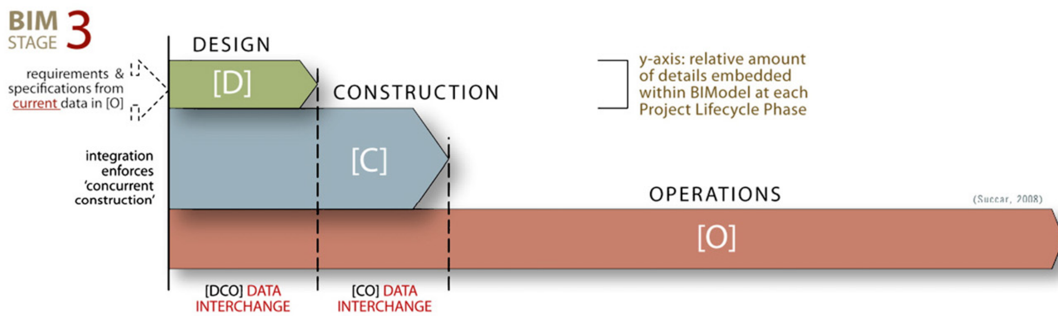


Fig. 12. Project Lifecycle Phases at BIM Stage 3 — linear model.

of analysis (Fig. 18) applied to Fields and Stages to generate 'Knowledge views' (refer to ontology, Section 3). They 'abstract' the BIM domain and control its complexity by removing unnecessary detail [45]. Lenses allow the domain researcher to selectively focus on any aspect of the AECO industry and generate knowledge views that either (a) highlight observables which meet the research criteria or (b) filter out those that do not. In essence, all knowledge views are abstractions derived from the application of one or more lenses and/or filters.

2.3.1. Differences between BIM Lenses and Filters

Lenses and Filters are investigative tools of enquiry and domain analysis allowing the discovery of concepts and relations (more about that in the Ontology Section 3). The difference between Lenses and Filters can be summarised as such: Lenses are additive and are deployed from the 'investigator's side' of BIM Field observation while Filters are subtractive and are deployed from the 'data side'. Lenses highlight observables that *meet* research criteria and identify their relations; example, an infrared lens highlights heat sources in a scene. Filters remove observables that *do not meet* the research criteria; example, data filters hides non-conforming data within a spreadsheet. Fig. 19 below visually exemplifies the difference between Lenses and Filters:

There are three types of lenses/filters which can be applied individually or collectively to generate a knowledge view:

2.3.2. Disciplinary Lenses and Filters

Disciplinary lenses generate BIM views through the application of fields of knowledge. If a discipline is applied as a filter, it will hide all data not related to that discipline from view. Table 5 below lists some applicable disciplinary lenses/filters:

The application of different disciplinary Lenses and Filters generate distinct views of the BIM domain. For example, when applying two different Lenses/Filters to a Stage 2 collaborative effort, two distinctly different knowledge views emerge:

- The application of a 'data management lens' highlights data flows and controls while a 'data flow filter' isolates exchanged file types.
- The application of a 'process management lens' highlights roles, procedures and tasks while a 'task filter' isolates specific meetings and phone calls.

2.3.3. Scoping Lenses and Filters

This type of Lens vary the horizontal and vertical abstraction [45] of the intended view. Scoping Lenses abstract the knowledge view by changing its granularity and filtering out unwanted information through 'rounding units of measurement'. Scoping lenses have three complexity levels [80]:

- A Macroscopic Lens: wide topical coverage but low in detail; example, a knowledge management lens depicting push–pull interactions between BIM Fields at industry level.
- A Mesoscopic Lens: medium coverage, focus and detail; example, a data management lens depicting inter-organisational data flows.
- A Microscopic Lens: narrow in focus but high in detail; example, a change management lens depicting the role of an individual driving BIM implementation within a team.

2.3.4. Conceptual Lenses and Filters

This type of Lens generates knowledge views by applying conceptual filters derived from the BIM Ontology — a specialised conceptual ontology developed by the author (refer to Section 3). Conceptual lenses/filters are not mutually exclusive and include: Agents, Constraints, Deliverables, Equipment, Tasks and Triggers to name a few.

In Summary, BIM Lenses and Filters — whether disciplinary, scoping or conceptual — can be applied individually or collectively to generate a host of views. This ability to extract knowledge views through abstraction and representation [61] provides the BIM Framework with flexibility and investigative granularity.

After introducing BIM Fields, Stags and Lenses, it is important to expand on the language employed by the Framework. Section 3 introduces a special ontology generated to 'systemically' expose the Framework's underlying knowledge structures, allow its modification and enable its extension. Section 4 follows by expanding on the 'visual language' critical for Framework's simplification, representation and dissemination.

3. An ontological representation of the BIM Framework

The BIM Framework aims to investigate and represent a host of concepts and relations. To reduce complexity, enable knowledge acquisition and validation of Framework's topics, a specialised 'conceptual' BIM Ontology has been developed.

The term ontology comes from Philosophy and signifies a systematic account of Existence [31] and "defines a common vocabulary for researchers who need to share information in a domain" [64]. There are many types of ontologies ranging in their formality, structure and intended use. The two main uses are to generate a language for communication *between people* [73,79] or interoperability *between systems* [79].

As a language to represent the BIM Framework, a BIM Ontology will act as a "formal description of the elements and relationships

Fig. 13. Step Sets leading to or separating BIM Stages — linear model.

between elements" within the domain [30]. It will also assist in the application of knowledge acquisition tools, techniques and methodologies [15], facilitate construction of domain models [73] and knowledge re-use across domains [30].

3.1. The BIM Ontology

For the purpose of representing the BIM Framework, the author has generated a specialised BIM Ontology by amending and reusing existing ones as recommended by Noy and McGuiness (2001). The selection of an existing ontology followed Gruber's criteria for shared ontologies — clarity, coherence, extensibility, minimal encoding bias and minimum ontological commitment — those intended for sharing knowledge and interoperation [30]. Based on these criteria, the BIM Ontology has been developed out of the General Technological Ontology [58,59] and the General Process Ontology [15].

The BIM Ontology comprises of four high level knowledge objects: concepts, attributes, relations and knowledge views (Table 6). This paper briefly discusses these levels in an effort to introduce — without fully exploring — the ontology's role in exposing, representing and further developing the Framework.

This BIM Ontology will be utilised to "analyse domain knowledge, make domain assumptions explicit, separate domain knowledge from the operational knowledge and enable reuse of domain knowledge" [64]. In addition to the specialised ontology, the BIM Framework will utilise 'abstracted representation' [45] to visualise BIM concepts and relations.

4. Visualising the BIM Framework

Driven by the expanse of knowledge domains covered by the BIM research framework, the knowledge transactions are necessarily numerous and complex in nature. Such a wide and varied knowledge scope necessitates the use of visualisation to cope with the amount and complexity involved [76] and offers a systematic way to transfer knowledge to others [23]. Using visualisation or 'graphical representation' expands the usability of data/information/knowledge following "universal laws that are unavoidable and undisputable but can be learned and taught" [8].

4.1. Using knowledge visualisation to represent the BIM Framework

Building Information Modelling includes transactions at the *data*, *information* and *knowledge* semantic levels. Representations of the BIM framework fall within the research area of knowledge visualisation; a merger between information visualisation, didactic techniques, visual cognition and visual communication [23]. Knowledge visualisation benefits from cognitive sciences' experimentation within the field of expertise and qualitative reasoning. It builds on the depiction of subject matter experts structuring their knowledge through qualitative mental models [69].

Knowledge visualisation utilizes graphical means to explore, communicate or resolve logical problems [12]. Visualisation can generate models in different formats (examples in Fig. 20) but share the intent to communicate and re-construct meaning [23].

Each model format offers a unique way to represent meaning. The VENN format (refer back to Fig. 3) is deemed appropriate by the author to best represent the overlapping nature of BIM Fields. In other instances, 'map-based' visualisations are better suited to represent BIM Framework's concepts, relations and ontological infrastructure (see Fig. 21).

According to Tergan (2003), map-based visualisation is a "valuable cognitive tool for supporting knowledge use in a variety of learning and instructional settings". Concept Maps — a specific type of map-based visualisations composed of nodes, links and labels — show high levels of acceptance when generated by domain experts [36]. Concept Maps are thus deployed to graphically represent the ontological relations between Framework parts. This combination of visual modelling driven by explicit ontological relations renders the Framework accessible to analysis, modification and extension.

After discussing the languages used — both ontological and visual — to expose, represent and communicate the BIM Framework, the next section explores some of its deliverables and research extensions.

5. BIM framework deliverables and extensions

The systemic subdivision of the BIM domain into Fields, Sub-Fields, Players, Deliverables, Stages, Steps, Lenses and Filters allow the generation of an array of deliverables. The Framework employs a simple yet specialised ontology to explore and 'make explicit' the relations between BIM concepts thus facilitating its semantic representation through a variety of mediums. The Framework is also served by a multitude of visual knowledge models which, in essence, simplify and clarify the overlapping BIM concepts to industry stakeholders. The Framework is arguably well placed to provide many deliverables — some of which are under development — classified by 'target audience' and 'scale of application'.

- Target audience: the BIM Framework is of benefit to both Industry and Academia. It generates knowledge modules, templates and tools that can assist in implementing and teaching BIM respectively.
- Scale of application: The BIM Framework — by virtue of its generic and systemic nature — is applicable across disciplines and lifecycle phases. Its deliverables can be scaled to guide BIM implementations within organisations, at project and industry levels.

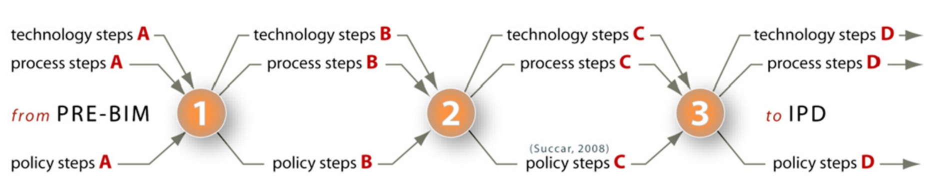


Fig. 14. Step Types leading to or separating BIM Stages — linear model.

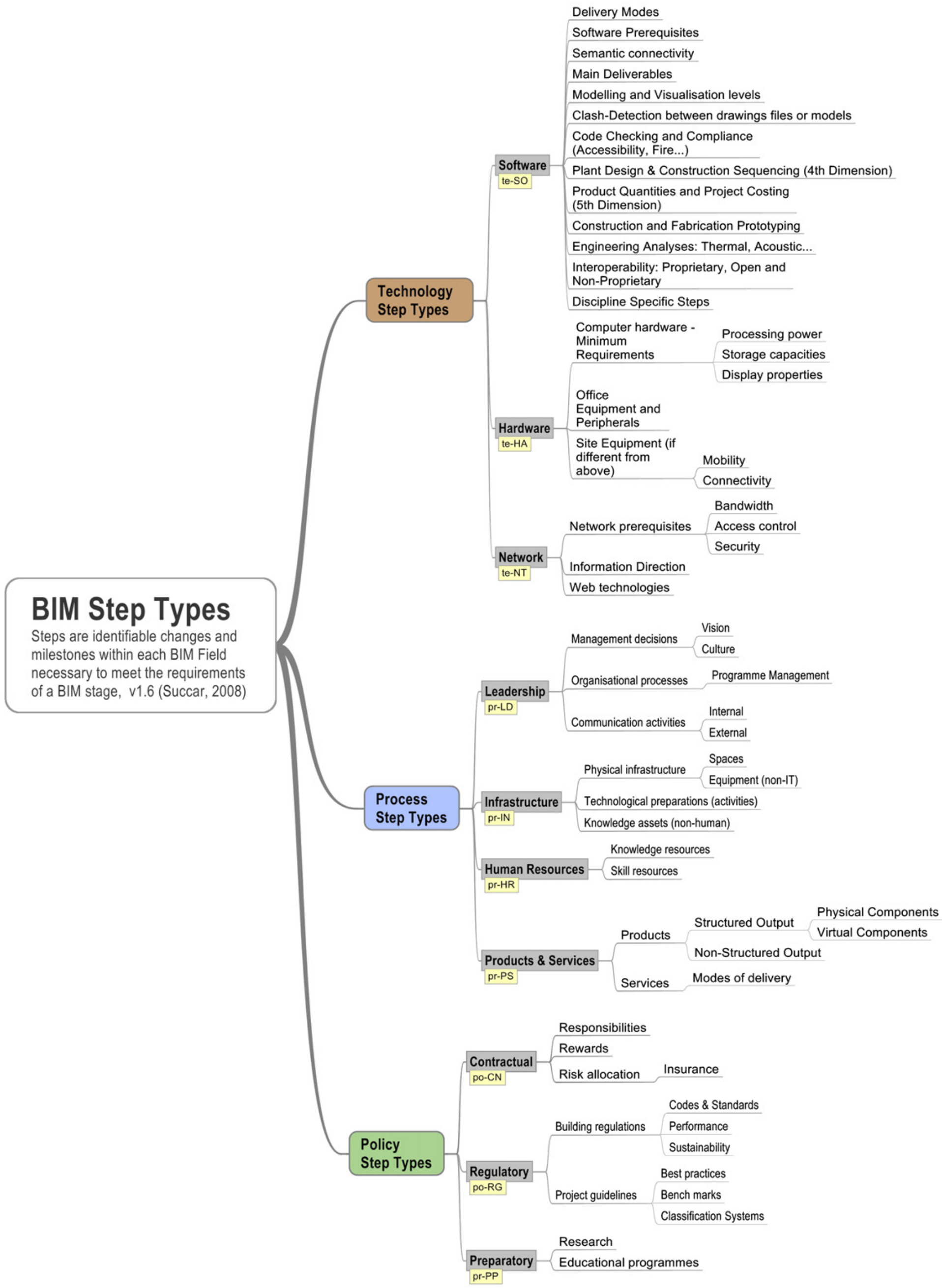


Fig. 15. Indicative and non-exhaustive list of BIM Step Types — mind map view.

Full exploration of Framework deliverables cannot be achieved within this 'scene-setting' paper. However, a summary of these deliverables is provided in Table 7 below:

5.1. Research extensions

The BIM Framework and its BIM Ontology provide an expandable base for knowledge acquisition, representation and sharing. Research extensions include generating visual knowledge models of many inter- and intra-organisational BIM Interactions. Push–pulls and Overlaps between BIM Fields can be visually and semantically represented and their knowledge components transformed into tools customised for different BIM Stages. The Framework can be contextualised to represent collaborative BIM relations between different industry players (ex: between an Architect and a Facility Manager) and extended to identify changing roles and emerging tasks

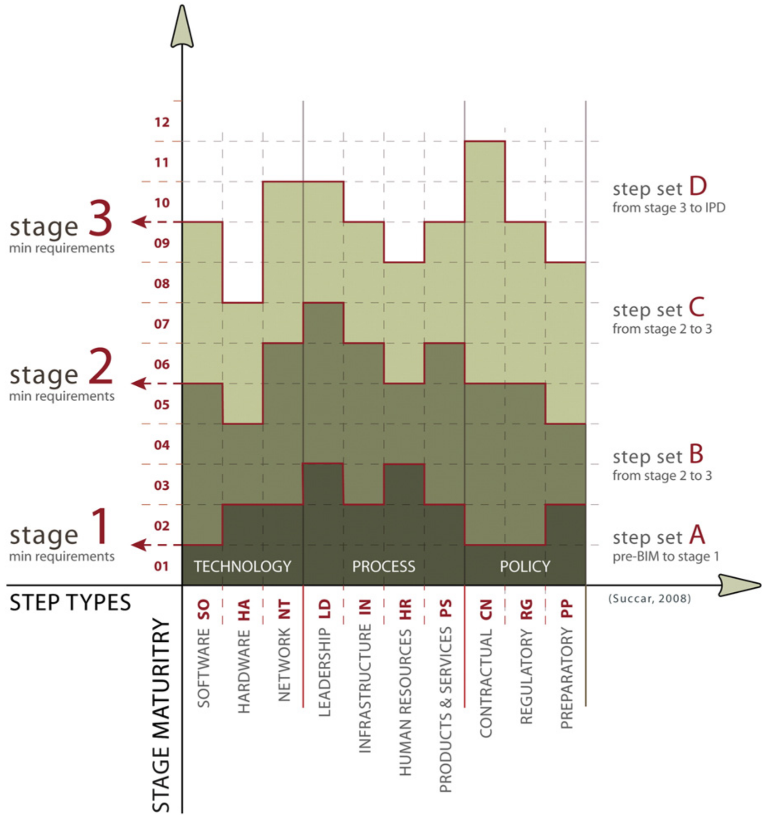


Fig. 16. Generic BIM Steps requirements for a BIM Stage — matrix view.

within organisations and teams. Finally, the Framework can be independently and collaboratively extended by subject matter experts using the BIM Ontology as a semantic structure and Concept Maps (for example) as a visual language.

6. A brief note on the methodology underlying the BIM Framework

Building Information Modelling is an expansive knowledge domain. To allow the Framework to systematically investigate and represent domain players, deliverables, interactions and maturity levels *and* render itself accessible to multiple investigators, the research methodology is necessarily a mixed one. Depending on the Framework part being investigated, validated or extended, the investigator will adopt the most appropriate paradigm, method or strategy irrespective if its inductive, deductive, retroductive or abductive nature [10]. In essence, the BIM Framework is generated and delivered through a mixed-method study [74].

A discussion of theoretical frameworks [3], methodology and investigation strategies underlying the BIM Framework cannot be adequately addressed in this paper. Nevertheless, a sample strategy to define one of the Framework's dimensions is briefly discussed below:

6.1. Sample research strategy: identifying BIM Fields

BIM Fields, one of three Framework dimensions, has been identified using 'conceptual clustering' of observable knowledge objects within the AECO industry. These clusters have been 'inductively inferred' through a strategy of observation and discovery [56].

Inductive inference is the "process of generating descriptions that imply original facts in the context of background knowledge" [56]. One key strategy to generate these descriptions is through observation and discovery where the observer analyses the background knowledge (the BIM landscape as an instance space) and determines that some observables can be usefully grouped. This act of grouping generates conceptual clusters of objects sharing common attributes.

According to Michalski and Stepp (1987), a 'concept' is an equivalence class of entities united by a common property or goal while 'clustering' is the act of grouping a collection of objects into classes [56]. Conceptual clustering thus signifies the identification of concepts, followed by classification of objects according to these concepts and, finally, the clustering of classified objects together. This process of identification, classification and clustering is goal-driven and attempts to simplify a large system by decomposing it into smaller sub-systems [57].

Inductive generalisation (whether instance-to-class *or* part-to-whole) and abduction (specific assertions based on background knowledge [56]) are two types of inductive inference techniques deployed to define some Framework concepts. For example, the AECO industry includes a great number of stakeholders. To cluster these stakeholders in a descriptive and useful manner, the Framework identifies a concept (BIM deliverables — a cluster in its own right), classifies stakeholders according to that concept and then, through an instance-to-class strategy, generates BIM Fields — a set of conceptual clusters (refer to Section 2.1).

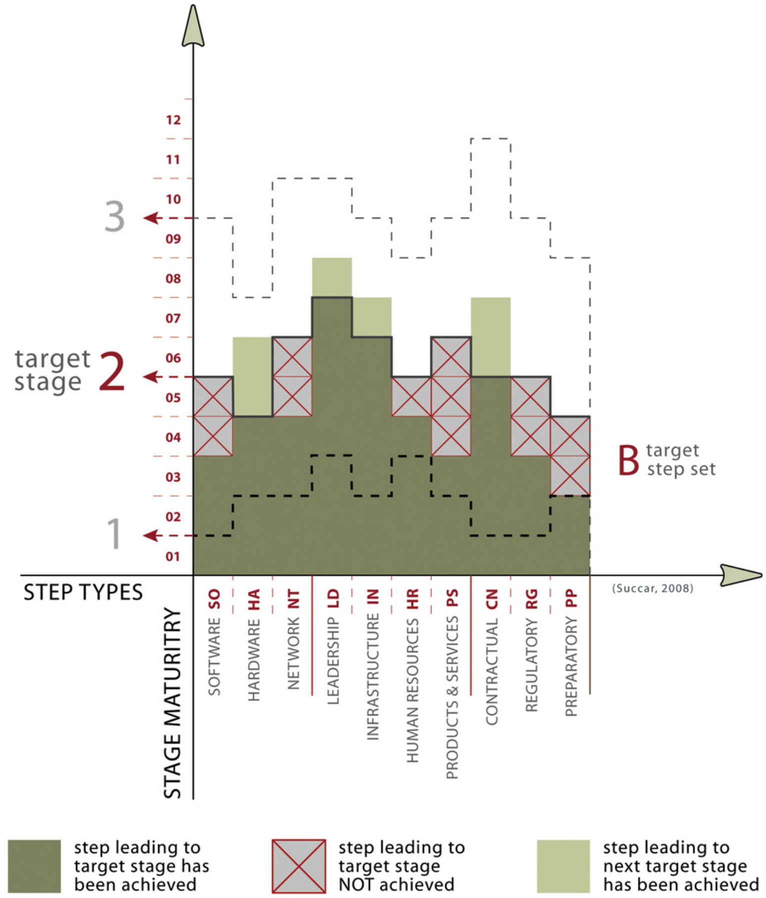


Fig. 17. Hypothetical assessment of an organisation using BIM Steps — matrix view.

Although inductive inference is a primary method for acquiring knowledge, creating new knowledge and even predicting future events [56], hypotheses generated by inductive inference need to be tested and verified before they become accepted theories.

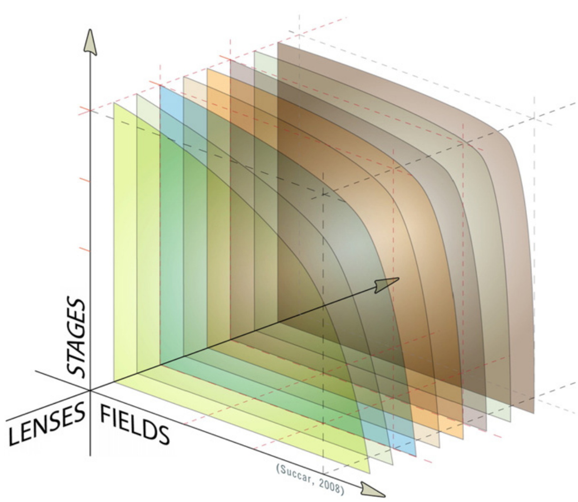


Fig. 18. BIM Lenses — tri-axial model.

6.2. Validation of the BIM Framework

The Framework aims to use multiple types of 'triangulation' — the observation of research issues from at least two different points [44] — to test and validate the accuracy of its subdivisions and their relations. Whether it is data, investigator, theory or methodological triangulation [19,66], the Framework will rely on available literature and new research (conducted by the author and others) using qualitative and quantitative paradigms, different methodologies and tailored investigative strategies.

7. Conclusion

Building Information Modelling is an expanding field of study incorporating many knowledge domains within the Architecture, Engineering, Construction and Operations industry. The divergence of study topics relating to BIM highlights the *necessity of* and *need for* a research framework to allow its systematic investigation. This paper has identified a research and delivery framework, specialised ontology and visual language tailored to investigate the BIM domain and provide actionable deliverables. This is a 'scene-setting' paper and many non-foundational framework parts have been excluded while others succinctly included; exclusions will be remedied in future

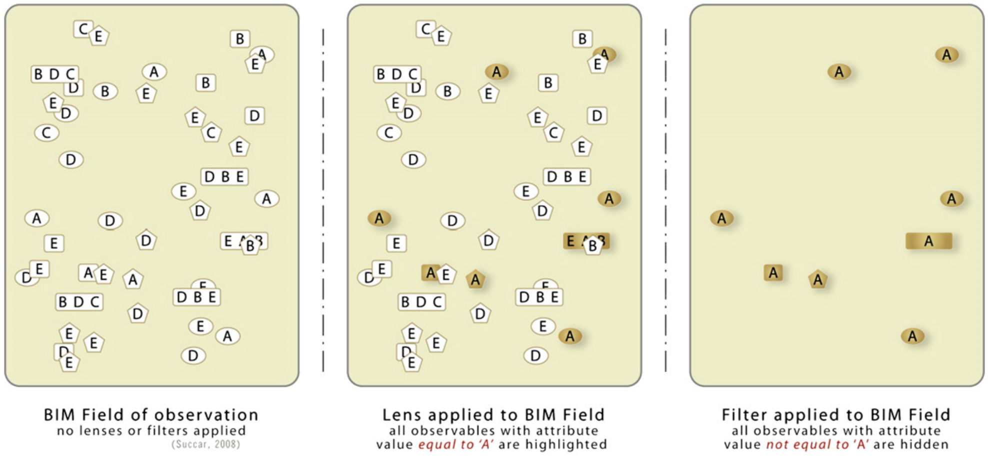


Fig. 19. Difference between BIM Lenses and Filters — tri-pane model.

publications. The BIM Framework is "an integrated framework [incorporating] different approaches to information within a consistent whole. It might incorporate not only the information model but also the reference process model and dictionaries. It is possible that it may go further and also enable the inclusion of ontology/taxonomy developments from the world of classification"[55].

In Summary, this paper has briefly introduced BIM Fields, BIM Stages and BIM Lenses. It also identified Step Sets, Step Types — both requisites of BIM implementation — and discussed many framework deliverables. Further investigations and publications are needed to generate a fuller understanding of the BIM domain and extend the Framework's research potential, academic standing and industrial deliverables.

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Table 5
A non-exhaustive matrix of BIM Lenses and Filters

Disciplinary BIM Lenses	Disciplinary BIM Filters
Change management	Change mechanisms, incentives, resistance,…
Construction/ project management	Project planning, resources, activities, …
Data management	Data standards, security, flows, …
Design management	Design leadership, communication, creativity, …
Financial management	Financial strategies, controls, budgets, …
Knowledge management	Knowledge acquisition, representation, transfer, …
Organisational behaviour	Organisational culture, development, planning, …
Process management	Process roles, procedures, tasks, …
Risk management	Risk identification, allocation, mitigation, …

Plus many other Disciplinary Lenses— like Human Resource Management, Product Management, Supply Chain Management, Quality Management — and their respective Filters. Disciplinary Lenses inherently overlap in their terminology and fields of application.

Table 6
Knowledge objects pertaining to BIM Ontology

Concepts			
Agents	Constraints	Deliverables	Equipment
Events	Examples	Functions	Human resources
Incentives	Information resources	Knowledge areas	Locations
Mental concepts	Organisational units	Physical phenomena	Products
Recommendations	Requirements	Results	Roles
Social	Social phenomena	Software agents	Software applications
Tasks	Triggers		
Attributes			
Category	Number	Link	Text
Relations			
Part of	Has part	Has expertise	Known by
Performs	Performed by	Uses	Used by
Supplies	Supplied by	Located in	Location of
Resource for	Has resource	Produces	Produced by
Owns	Owned by	Causes	Caused by
Runs	Run by	Attends	Attended by
Has function	Function of	Documented in	Describes
Requires	Required by	Consults	Consulted by
Made of	Material for	Followed by	Involves
Has role	Has contact	Applicable to	Occupied by
Affects	Linked to	Has authority over	Is empowered by
Validates	Is validated by		
Knowledge views			
Knowledge document	Knowledge matrix	Knowledge model	Knowledge store

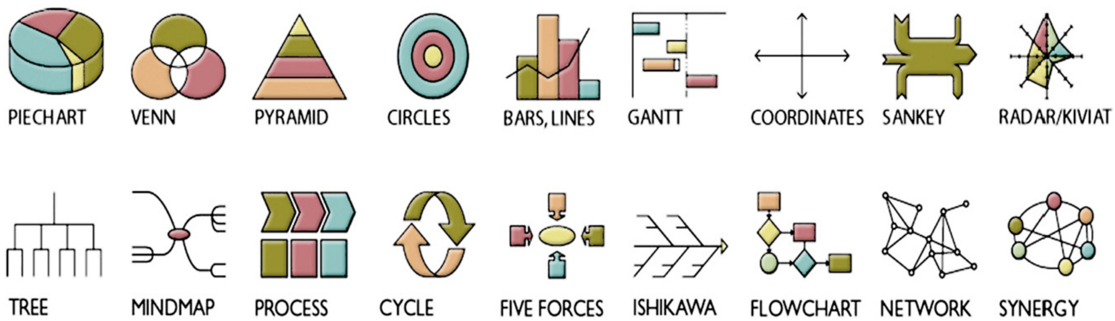

Fig. 20. Sample visualisation models — adapted from Eppler and Burkhard [23].

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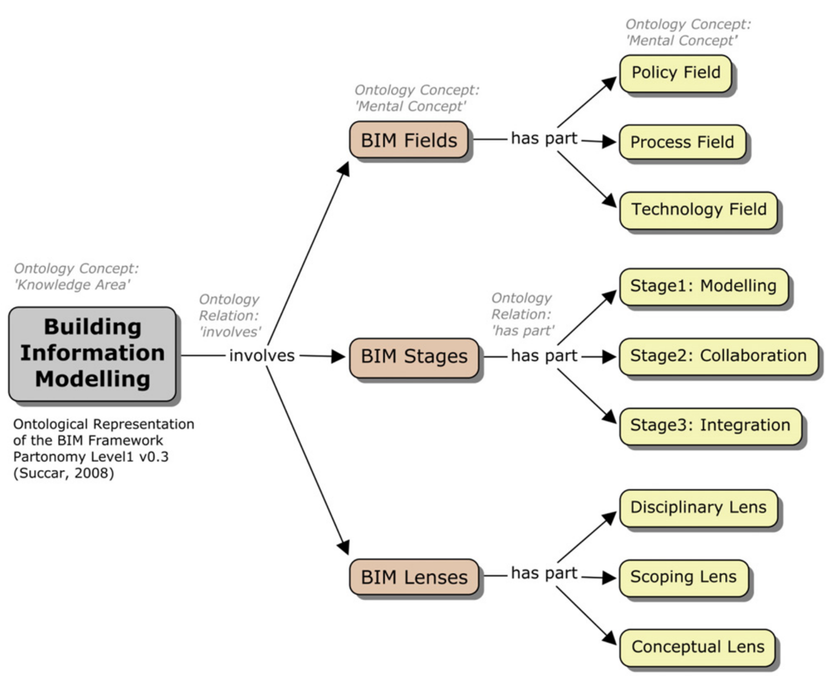

Fig. 21. Knowledge view using Concept Maps and BIM Ontology.

Table 7
Summary matrix of BIM Framework deliverables

Deliverables	Macroscopic: industry level	Mesoscopic: project level	Microscopic organisation level
	Multiple disciplines	Multiple organisations	Individuals and teams
Educational deliverables	Generating BIM Literacy Guidelines, producing learning tools and collating case studies — through publication of a BIM textbook	Identifying BIM Educational Deliverables according to organisational types and delivery modes — example: identifying vocational, tertiary, industry and industry associations' BIM educational deliverables	Classifying and embedding BIM Educational Deliverables into different curricula and the generation of BIM educational tools — example: developing course outlines and learning plans for an undergraduate course
Industry deliverables	Setting an industry-centric BIM Knowledge Store catering for organisations and individuals — through the publication of industry papers and setting up a BIM-focused wiki and a weblog	Generating BIM Implementation Guidelines in modular format detailing BIM Maturity Steps within and across industry disciplines — examples: BIM leadership, risk management and HR development modules	Generating a BIM Implementation Handbook in modular format including implementation templates and change tools — example: a BIM Skill/ Knowledge Competency Matrix for staff or a BIM Software Selection Matrix

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PAPER A3

Building Information Modelling Maturity Matrix

Succar, B. (2010). Building Information Modelling Maturity Matrix. In J. Underwood & U. Isikdag (Eds.), *Handbook of Research on Building Information Modelling and Construction Informatics: Concepts and Technologies* (pp. 65-103): Information Science Reference, IGI Publishing.

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Building Information Modelling Maturity Matrix

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ChangeAgents AEC, Australia

ABSTRACT
Building Information Modelling (BIM) is an expanding collection of concepts and tools which have been attributed with transformative capabilities within the Architecture, Engineering, Construction and Operations (AECO) industry. BIM discussions have grown to accommodate increasing software capabilities, infinitely varied deliverables, and competing standards emanating from an abundance of overlapping definitions attempting to delineate the BIM term. This chapter will steer away from providing its own definition of BIM yet concurs with those identifying it as a catalyst for change (Bernstein, 2005) poised to reduce industry's fragmentation (CWIC, 2004), improve its efficiency (Hampson & Brandon, 2004) and lower its high costs of inadequate interoperability (NIST, 2004). In essence, BIM represents an array of possibilities and challenges which need to be understood and met respectively through a measurable and repeatable approach.
This chapter briefly explores the multi-dimensional nature of the BIM domain and then introduces a knowledge tool to assist individuals, organisations and project teams to assess their BIM capability, maturity and improve their performance (Figure 1).

The first section introduces BIM Fields and Stages which lay the foundations for measuring capability and maturity. Section 2 introduces BIM Competencies which can be used as active implementation steps or as performance assessment areas. Section 3 introduces an Organisational Hierarchy/Scale suitable for tailoring capability and maturity assessments according to markets, industries, disciplines and organisational sizes. Section 4 explores the concepts behind 'capability maturity models' and then adopts a five-level BIM-specific Maturity Index (BIMMI). Section 5 introduces the BIM Maturity Matrix (BIm³), a performance measurement and improvement tool which identifies the correlation between BIM Stages, Competency Sets, Maturity Levels and Organisational Scales. Finally, Section 6 introduces a Competency Granularity Filter which enables the tailoring of BIM tools, guides and reports according to four different levels of assessment granularity.

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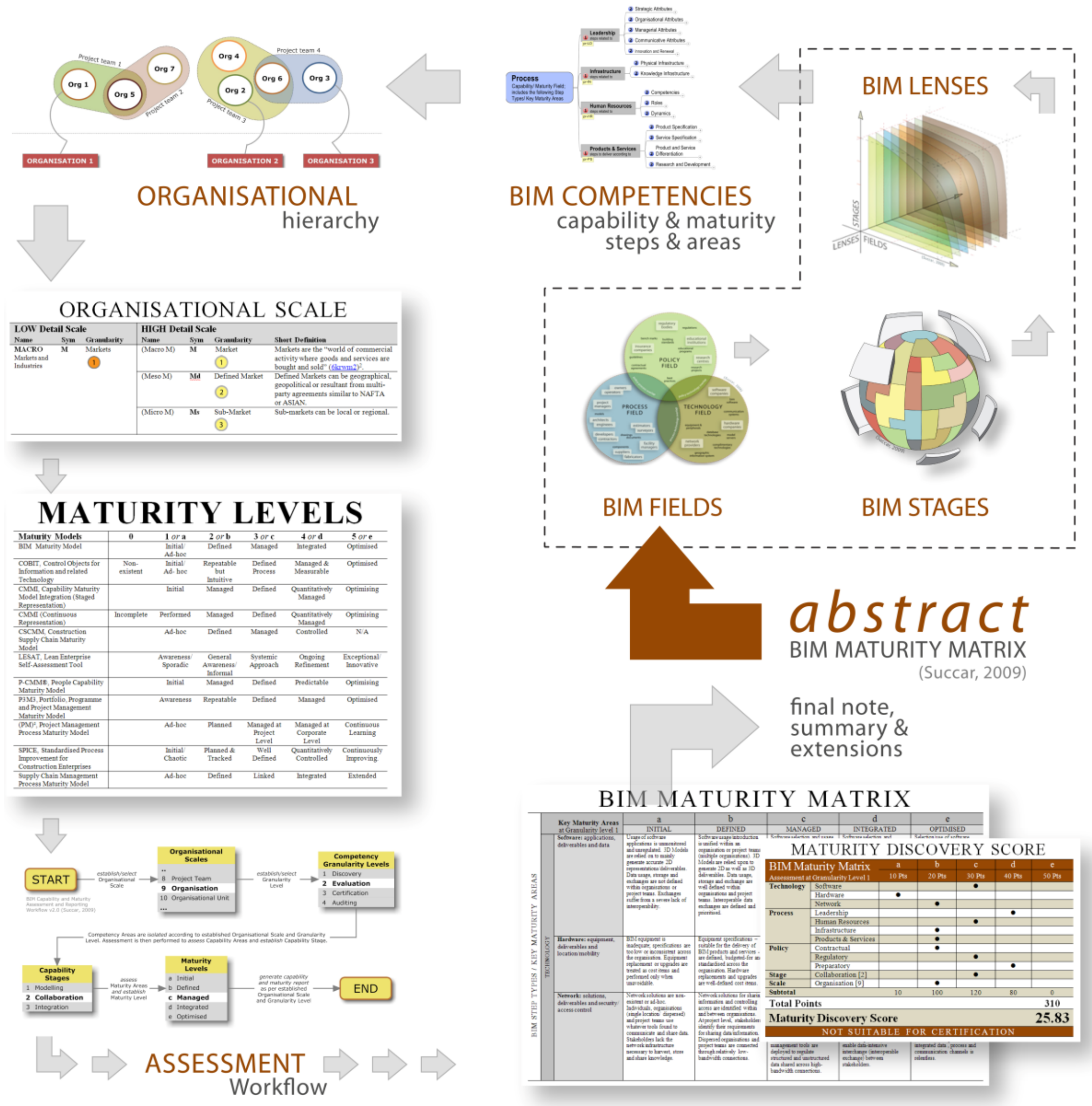


Figure 1. Visual Abstract

1 Building Information Modelling: a brief introduction

Building Information Modelling is a set of interacting policies, processes and technologies (Succar, 2009) generating a "methodology to manage the essential building design and project data in digital format throughout the building's life-cycle" (Penttilä, 2006). This definition is one of tens of attempts to delimit the BIM domain which - as a term- continues to expand in coverage and connotation. It is important – if we acknowledge BIM's value in assisting the AECO industry and are inclined to assist in its systematic adoption - to identify the domain's knowledge structures, internal dynamics and implementation requirements. These can be best represented through a tri-axial understanding of the BIM domain (Figure 2):

- *BIM Fields* of activity identifying domain 'players', their 'requirements' and 'deliverables'.
- *BIM Stages* delineating minimum capability benchmarks.
- *BIM Lenses* providing the depth and breadth of enquiry necessary to identify, assess and qualify BIM Fields and BIM Stages.

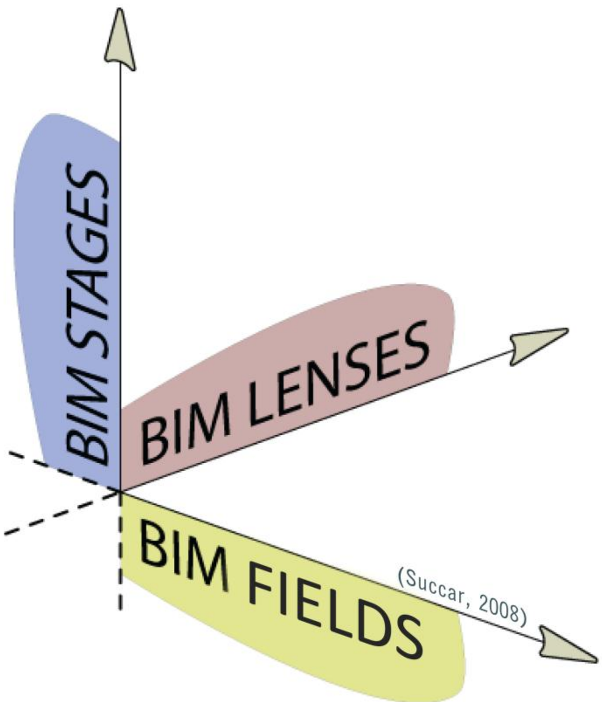


Figure 2. BIM framework: Fields, Stages and Lenses – tri-axial model

BIM Fields

The BIM domain is comprised of three interlocking yet distinctive *fields of activity* (Figure 3): Technology, Process and Policy. Each one of these BIM fields has its own players, requirements and deliverables. BIM players can be individuals, teams, organisations or other groupings as discussed later in Section 3.

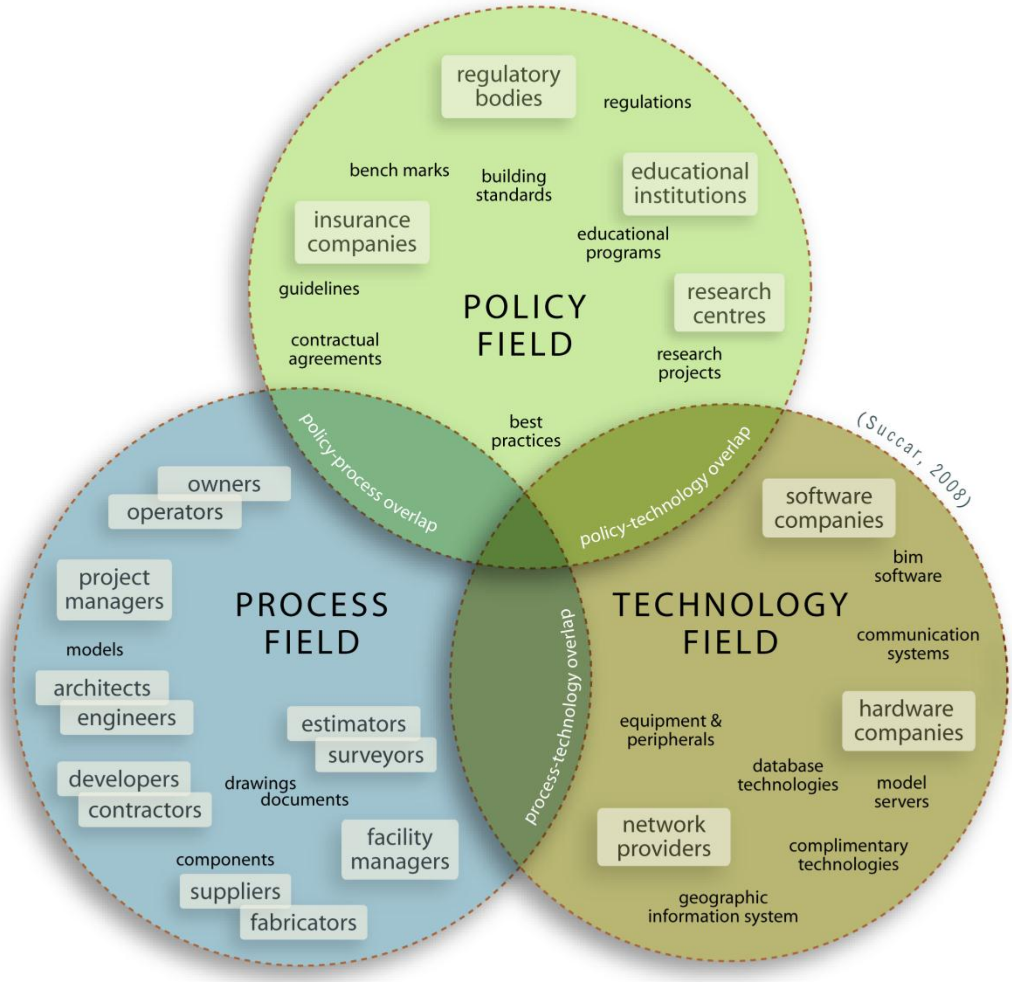
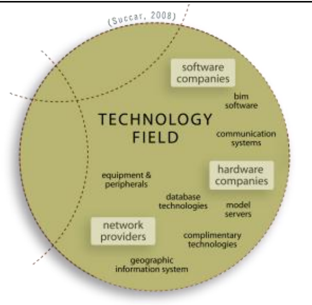
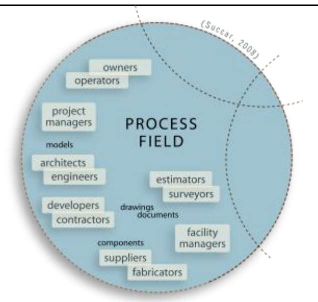
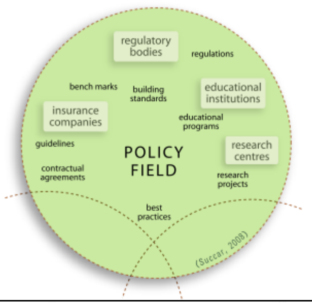
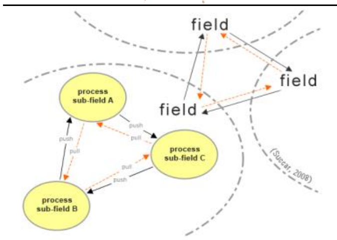
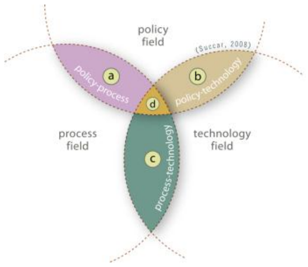


Figure 3. Three interlocking Fields of BIM activity– venn diagram

BIM Fields have been identified using 'conceptual clustering' of observable knowledge objects within the AECO industry. These clusters have been 'inductively inferred' through a strategy of observation and discovery (Michalski, 1987). The three BIM Fields interact within the AECO industry generating new products, services and roles. Table 1 summarises each of the three fields, their interactions and overlaps:

Table 1. BIM Fields, their interactions and overlaps

<table>
<tr><th colspan="2">BIM FIELDS</th></tr>
<tr><td>
</td><td>The Technology Field clusters a group of players who specialise in developing software, hardware, equipment and networking systems necessary to increase efficiency, productivity and profitability of AECO sectors. These include organisations which generate software solutions and equipment of direct and indirect applicability to the design, construction and operation of facilities.</td></tr>
<tr><td>
</td><td>The Process Field clusters a group of players who procure, design, construct, manufacture, use, manage and maintain structures. These include facility owners, architects, engineers, contractors, facility managers and all other AECO industry players involved in the ownership, delivery and operations of buildings or structures.</td></tr>
<tr><td>
</td><td>The Policy Field clusters a group of players focused on preparing practitioners, delivering research, distributing benefits, allocating risks and minimising conflicts within the AECO industry. These players do not generate any construction products but are specialised organisations - like insurance companies, research centres, educational institutions and regulatory bodies – which play a pivotal preparatory, regulatory and contractual roles in the design, construction and operations process.</td></tr>
<tr><td>
</td><td>BIM Interactions are push-pull knowledge transactions occurring within or between fields. Push mechanisms (Holsapple & Joshi, 2006) transfer knowledge from one player or field to another while pull mechanisms transfer knowledge to satisfy a request by another player or field. Sample transactions include data transfers, team dynamics and contractual relationships between fields and their players.</td></tr>
<tr><td>
</td><td>The three distinct fields overlap as they share players, requirements and deliverables. These BIM Overlaps between fields are exemplified in two cases below:

Case 1: when a BIM deliverable requires input from two or more players or fields. For example, the development and implementation of non-proprietary interoperable schema (like Industry Foundation Classes) necessitates the joint effort of Policy players (researchers) as well as Technology players (software developers).

Case 2: when players pertaining to one field generate deliverables classified in another. For example, the Australian Institute of Architects is an ‘industry body’ - whose members are Process players (architects) - generating Policy deliverables (guidelines and best practices).</td></tr>
</table>

BIM Stages

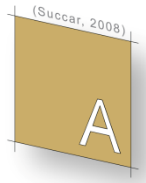
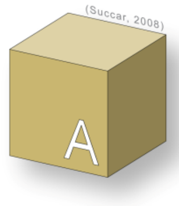
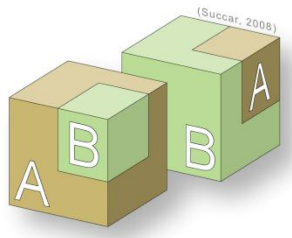
There are voluminous possibilities attributed to BIM representing an array of challenges which need to be addressed by Architecture, Engineering, Construction and Operations (AECO) stakeholders. Having identified the BIM Fields, this section identifies the multiple stages which delineate capability milestones.

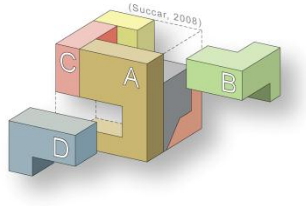
BIM capability is the *basic ability* to perform a task, deliver a service or generate a product. BIM Capability Stages (or BIM Stages) define the major milestones to be achieved by teams and organisations as they adopt BIM technologies and concepts. BIM Stages identify a fixed starting point (the status before BIM implementation), three fixed BIM stages and a variable ending point which allows for unforseen future advancements in technology. This chapter uses the term Pre-BIM to represent industry status prior to BIM implementation and Integrated Project Delivery (IPD) to denote an *approach to* or an *ultimate goal of* implementing BIM (AIA, 2007). BIM Stages include technology, process and policy components and are as follows:

- *BIM Stage 1:* object-based modelling
- *BIM Stage 2:* model-based collaboration
- *BIM Stage 3:* network-based integration

BIM Stages are defined by their *minimum requirements*. As an example, for an organisation to be considered at BIM Capability Stage 1, it needs to have deployed an object-based modelling software tool. Similarly for BIM Capability Stage 2, an organisation needs to be part of a multidisciplinary model-based collaborative project. To be considered at BIM Capability Stage 3, an organisation must be using a network-based solution (like a model server) to share object-based models with at least two other disciplines. Table 2 expands on the above BIM Capability Stages starting with Pre-BIM and ending with a brief description of Integrated Project Delivery (IPD):

Table 2. Pre-BIM, BIM Capability Stages and Integrated Project Delivery

BIM CAPABILITY	
Pre-BIM status *Disjointed Project Delivery* 	The construction industry is characterised by adversarial relationships where contractual arrangements encourage risk avoidance and risk shedding. Much dependence is placed on 2D documentation to describe a 3D reality. Even when some 3D visualisations are generated, these are often disjointed and reliant on two-dimensional documentation and detailing. Quantities, cost estimates and specifications are generally neither derived from the visualisation model nor linked to documentation. Similarly, collaborative practices between stakeholders are not prioritised and workflow is linear and asynchronous. Under pre-BIM conditions, industry suffers from low investment in technology and lack of interoperability (CWIC, 2004) (NIST, 2004). *The graphical symbol (left) represents 2D hand-drawn, 2D computer-aided drafting or 3D non-object based software technologies similar to AutoCAD® and SketchUP®.*
BIM Stage 1 *Object-based Modelling*  *The graphical symbol above represents a single-disciplinary 3D model exemplified by an architect's ArchiCAD®, a structural engineer's Revit® or a steel detailer's Tekla® model.*	BIM implementation is initiated through the deployment of an 'object-based 3D parametric software tool' similar to ArchiCAD®, Revit®, Digital Project® and Tekla®. At Stage 1, users generate single-disciplinary models within either design [D], construction [C] or operations [O] – the three Project Lifecycle Phases. Modelling deliverables include architectural design models [D] and duct fabrication models [C] used primarily to automate generation and coordination of 2D documentation and 3D visualisation. Other deliverables include basic data exports (e.g. door schedules, concrete volumes, FFE costs,...) and light-weight 3D models (e.g. 3D DWF, 3D PDF, NWD, etc...) which have no modifiable parametric attributes. Collaborative practices at Stage 1 are similar to pre-BIM status and there are no significant model-based interchanges between different disciplines. Data exchanges between project stakeholders are uni-directional and communications continue to be asynchronous and disjointed. As only minor process changes occur at Stage 1, pre-BIM contractual relations, risk allocations and organisational behaviour persist. However, the semantic nature of object-based models and their 'hunger' for early and detailed resolution of design and construction challenges encourage 'fast-tracking' of Project Lifecycle Phases - when a project is still executed in a phased manner yet design and construction activities are overlapped to save time (Jaafari, 1997).
BIM Stage 2 *Model-based Collaboration*  *The graphical symbol (above) represents the interchange of 3D models between two different disciplines (A and B). This can be exemplified by two-way linking of Revit® Architectural and Structural models (a proprietary interoperable exchange) or the interchange of IFC- files exported out of multi-disciplinary BIM applications (a non-proprietary interoperable exchange).*	Having developed single-disciplinary modelling expertise during Stage 1 implementations, Stage 2 players actively collaborate with other disciplinary players. Collaboration may occur in several technical ways following each player's selection of BIM software tools. Two different examples of model-based collaboration include the interchange (interoperable exchange) of models or part-models through 'proprietary' formats (e.g. between Revit® Architecture and Revit® Structure through the .RVT file format) and non-proprietary formats (e.g. between ArchiCAD® and Tekla® using the IFC file format). Model-based collaboration can occur within one or between two Project Lifecycle Phases. Examples of this include the Design-Design interchange of architectural and structural models [DD], the Design-Construction interchange of structural and steel models [DC] and the Design-Operations interchange of architectural and facility maintenance models [DO]. It is important to note that only one 'collaborative model' needs to hold 3D geometric data to allow for semantic BIM interchanges between two disciplines. An example of this is the [DC] interchange between a 3D object-based model (e.g. Digital Project®), scheduling database (e.g. Primavera® or MS project®) or a cost estimating database (e.g. Rawlinsons or Timberline®). Such interchanges allow the generation of 4D (time analysis) and 5D (cost estimating) studies respectively. Although communications between BIM players continue to be asynchronous, pre-BIM demarcation lines separating roles, disciplines and lifecycle phases start to fade. Some contractual amendments become necessary as model-based interchanges augment and start replacing document-based workflows. Stage 2 also alters the granularity of modelling performed at each lifecycle phase as higher-detail construction models move forward and replace (partially or fully) lower-detail design models.

BIM Stage 3 *Network-based Integration* 	At this capability stage, semantically-rich integrated models are created, shared and maintained collaboratively across Project Lifecycle Phases. This integration can be achieved through 'model server' technologies (using proprietary, open or non-proprietary formats), single-integrated/distributed-federated databases (Bentley, 2003) (Liaserin, 2003), Cloud Computing or SaaS (Software as a Service)(Wilkinson, 2008). BIM Stage 3 models become interdisciplinary nD models (Lee et al., 2003) allowing complex analyses at early stages of virtual design and construction. At this Stage, model deliverables extend beyond semantic object properties to include business intelligence, lean construction principles, green policies and whole lifecycle costing. Collaborative work now 'spirals iteratively' around an extensive, unified and sharable data model (Edgar, 2007). From a process perspective, synchronous interchange of model and document-based data cause project lifecycle phases to overlap extensively forming a phase-less process.

The graphical symbol (above) represents the integration of 3D models using a network-based technology. Each of the single-disciplinary models (represented by capital letters) is an integral part of the resulting inter-disciplinary model.

Integrated Project Delivery *Interdependent, real-time models* 	Integrated Project Delivery, a term popularised by the American Institute of Architects California Council (AIA, 2007) is, in the author's view, suitable for representing a long-term vision of BIM as an amalgamation of domain technologies, processes and policies. The term is generic enough and potentially more readily understandable by industry than "Fully Integrated and Automated Technology" (FIATECH, 2005), Integrated Design Solutions (İLAL, 2007) or "nD Modelling" (Lee et al., 2003) as three prominent examples. The selection of Integrated Project Delivery (IPD) as the 'goal' of BIM implementations is not to the exclusion of other visions appearing under different names. On the contrary, the path from Pre-BIM (a fixed starting point), passing through three well defined Stages towards a loosely defined IPD is an attempt to include all pertinent BIM visions irrespective of their originating sources.

The graphical symbol (above) represents the delivery and continuous evolution of a highly integrated multi-dimensional model connected to multiple external databases and knowledge sources in real-time. These include services' grid, building management systems, geographic information systems (GIS), cost databases, operations business logic, etc...

BIM Lenses

BIM Lenses are distinctive layers of analysis (Figure 4) applied to Fields and Stages to generate *knowledge views* which 'abstract' the BIM domain and control its complexity by removing unnecessary detail (Kao & Archer, 1997). Lenses allow domain researchers to selectively focus on any aspect of the AECO industry and generate knowledge views that either (a) highlight observables which meet the research criteria or (b) filter out those that do not. In this chapter, a 'scoping' lens/filter (Succar, 2009) will be transparently applied to identify Organisational Scales (Section 3) and assessment Granularity Levels (Section 5).

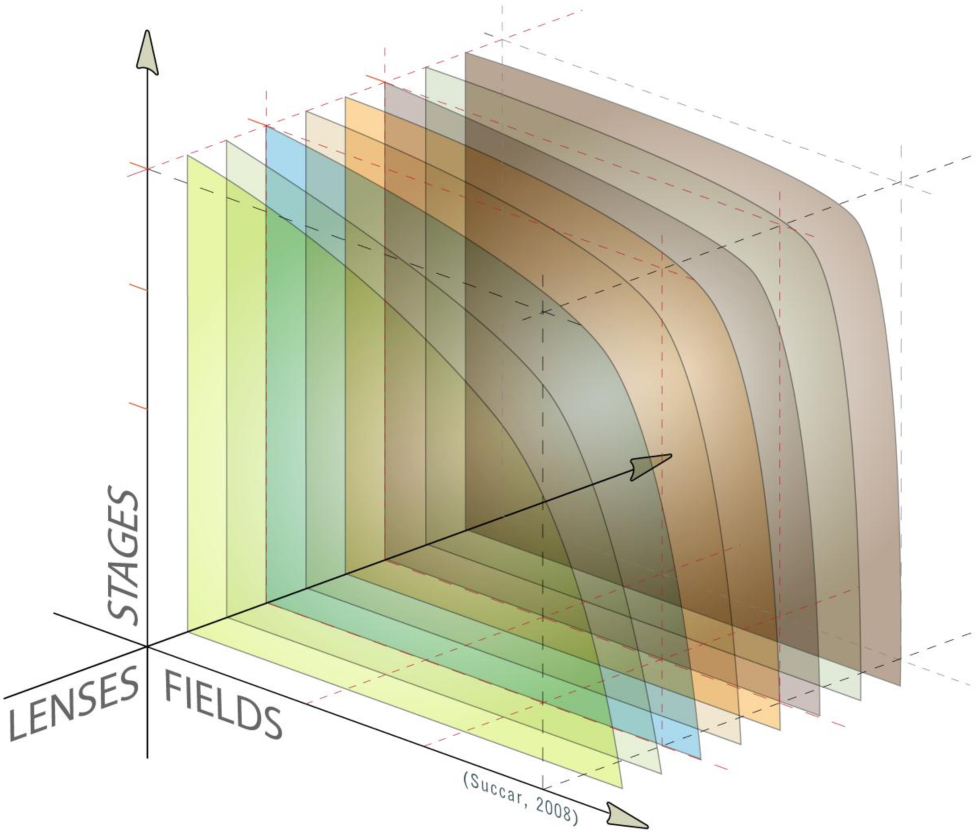


Figure 4. BIM Lenses – tri-axial model

2 BIM Competency Sets

A BIM Competency represents a BIM Player's ability to satisfy a BIM Requirement or generate a BIM Deliverable. A BIM Competency Set is a hierarchical collection of individual competencies identified for the purposes of BIM implementation and assessment. BIM Competency Sets follow the same classification as BIM Fields and are explored in Figure 5. A short description is also provided below:

- *Technology Sets* in *software, hardware* and *networks.* For example, the availability of a BIM tool allows the migration from drafting-based to object-based workflow (BIM Stage 1)
- *Process Sets* in *Leadership, Infrastructure, Human Resources* and *Products/Services.* For example, collaboration processes and database-sharing skills are necessary to allow model-based collaboration (BIM Stage 2).
- *Policy Sets* in *contracts, regulations* and *research/education.* For example, alliance-based and risk-sharing contractual agreements are pre-requisites to network-based integration (BIM Stage 3).

BIM Competencies are employed to establish BIM *Capability* or BIM *Maturity*[ii] benchmarks. They can also be used by teams and organisations to either *implement* BIM or *assess* its implementation. If BIM Competencies are used for the purposes of active implementation[iii], then they are referred to as BIM Steps. However, if they are used for assessing existing implementations, then they are referred to as BIM Areas. Not all BIM Competencies are of the same significance and can thus be separated into Key and non-Key Competencies.

[ii] The term *capability* in this chapter refers to the 'basic ability to perform a task' while the term *maturity* refers to the 'degrees of excellence in performing that task'(refer to Section 4).

[iii] This chapter uses an expanded definition of the term 'implementation'. Throughout this chapter, BIM implementation *does not only reflect the act of deploying* software, schema and their related processes but *represents all actions necessary to achieve, maintain and increase* BIM Capability and Maturity.

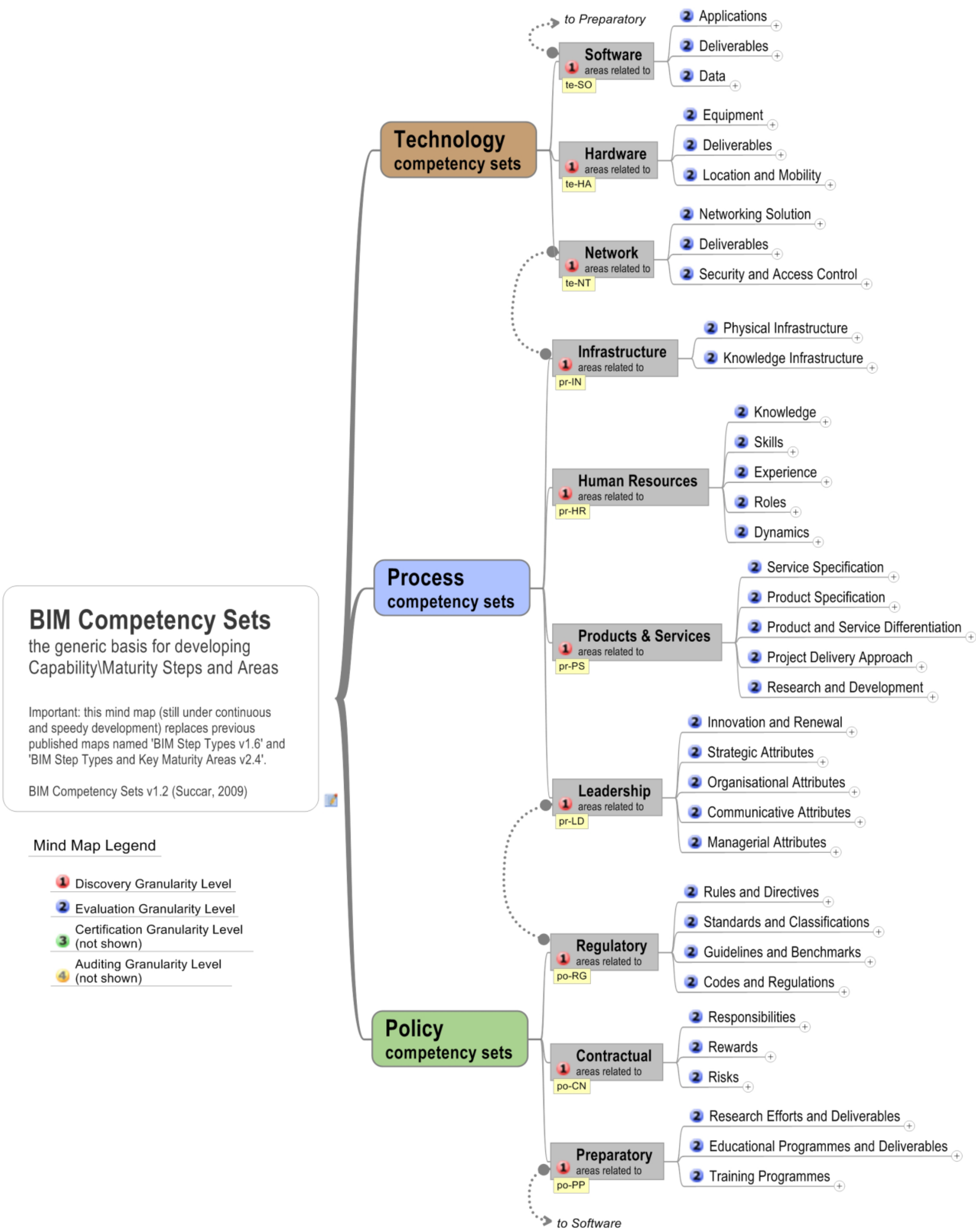


Figure 5. Indicative list of BIM Competency Sets v1.2 – mind map at Granularity Level 2

BIM Steps

The volume and complexity of changes required to achieve each of the three BIM Stages (refer to Table 2) are *transformational* and even *radical* (Henderson & Clark, 1990) (Taylor & Levitt, 2005). However, the passage from Pre-BIM to BIM Stage 1, through each of the three Stages and towards Integrated Project Delivery is populated by *incremental* or *evolutionary* steps. Identifying these BIM Steps is instrumental in enabling organisations and individuals to increase their BIM capability and maturity in a systematic way. Each BIM Stage has its own requirements and deliverables giving rise to numerous BIM Steps. These are collated into 'sets' according to their location on the implementation continuum (Figure 6):

- *A Steps:* from pre-BIM leading to BIM Stage 1
- *B Steps:* from BIM Stage 1 leading towards BIM Stage 2
- *C Steps:* from BIM Stage 2 leading towards BIM Stage 3
- *D Steps:* from BIM Stage 3 leading towards Integrated Project Delivery

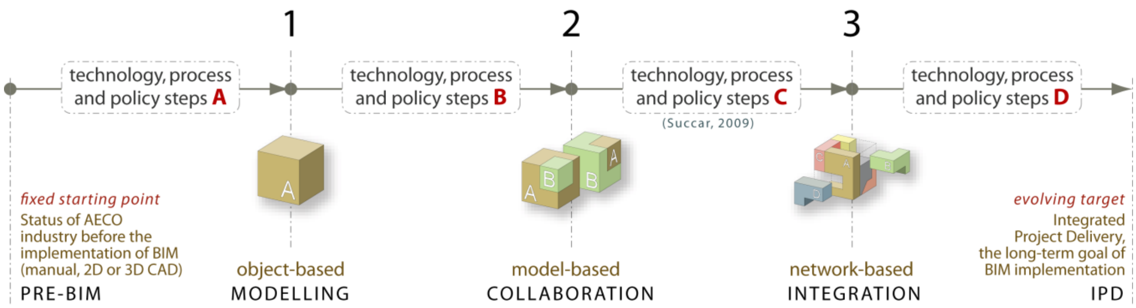


Figure 6. Step Sets leading to or separating BIM Stages – linear model v1.0

3 BIM Organisational Hierarchy

In the construction industry, every building, road or bridge construction project is a *unique* prototype involving a *similar* set of process stages (Wegelius-Lehtonen, 2001). This uniqueness, on one hand, is driven by multiple factors including the transient nature of project teams and the distinctive locational and environmental criteria of each project site. The similarity, on the other hand, is driven by long-held views of how construction projects should be conducted, reasonably stable organisational structures, slow-changing educational concepts and risk-averse insurance policies. This challenging duality of 'uniqueness' and 'similarity' is addressed by the BIM Framework through the development of an Organisational Hierarchy (Figure 7) and a granular Organisational Scale (Table 3). Both the Hierarchy and the Scale are based on the notions of *flexibility* - to cater for 'uniqueness' - and *uniformity* to cater for 'similarity':

- *Flexibility (of application):* BIM Capability and Maturity assessments can apply irrespective of organisational size, project type or how a project team is configured.

- *Uniformity (of measurement):* BIM Capability and Maturity assessments can be based on a set of standardised organisational subdivisions. Assessment results pertaining to an organisational unit, an organisation or a project team can be uniformly and respectively compared to another same-scale unit, organisation or project team.

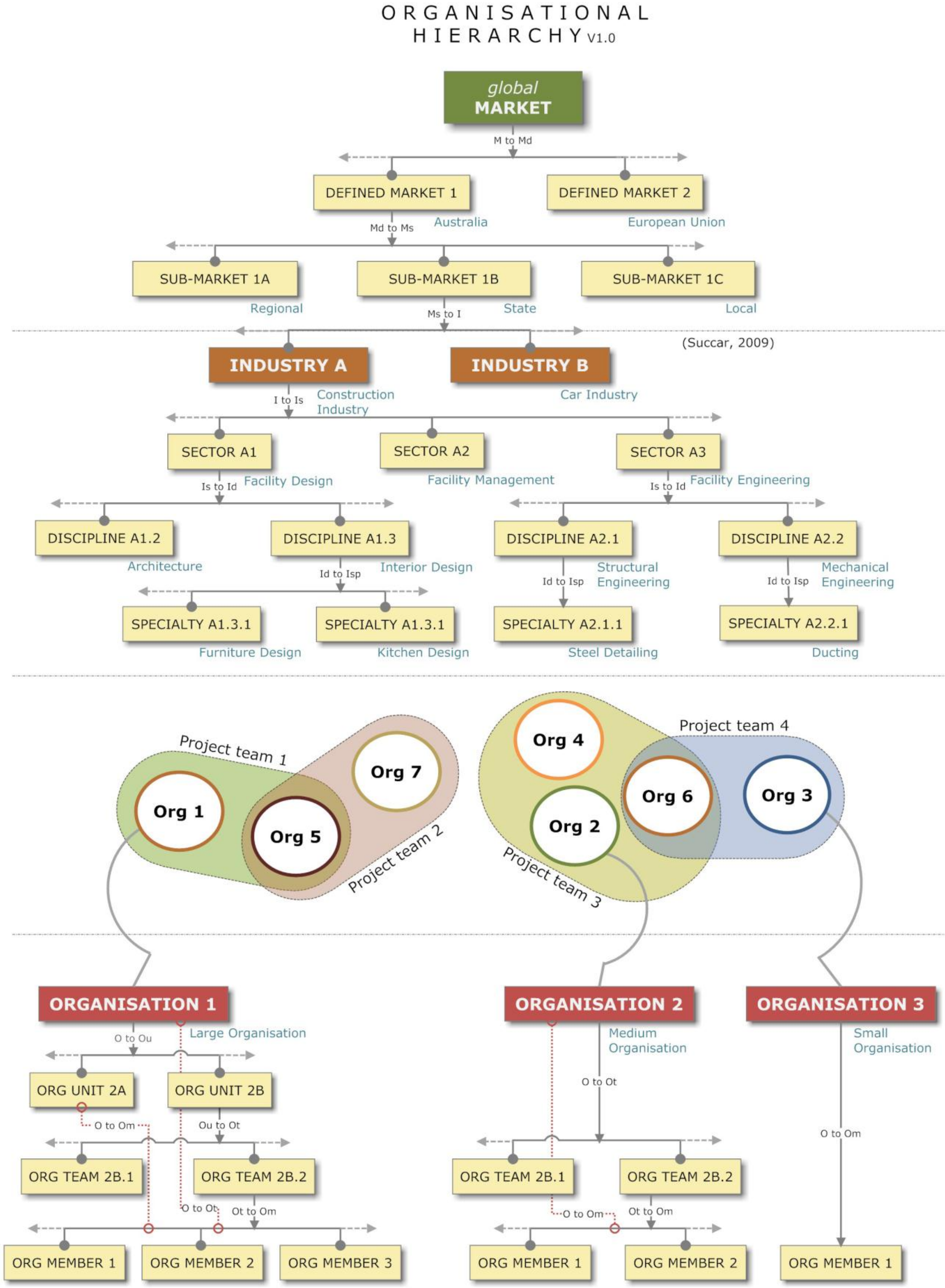


Figure 7. Organisational Hierarchy used for BIM Maturity – Tree view v1.0

Table 3 elaborates on the Organisational Hierarchy and introduces a granular scale. Acting as a BIM 'scoping filter' (Succar, 2009) the Organisational Scale (OScale) can be applied to BIM Players enabling a more-targeted approach to BIM implementation and assessment:

Table 3. Granular Organisational Scale

ORGANISATIONAL SCALE

Low Detail			High Detail			
Name	**Sym**	**Granularity**	**Name**	**Sym**	**Granularity**	**Short Definition**
MACRO Markets and Industries	**M**	Markets 1	(Macro M)	**M**	Market 1	Markets are the "world of commercial activity where goods and services are bought and sold" http://bit.ly/pjB3c
			(Meso M)	**Md**	Defined Market 2	Defined Markets can be geographical, geopolitical or resultant from multi-party agreements similar to NAFTA or ASIAN.
			(Micro M)	**Ms**	Sub-Market 3	Sub-markets can be local or regional.
	I	Industries 4	(Macro I)	**I**	Industry 4	Industries are 'the organized action of making of goods and services for sale'. Industries can traverse markets and may be service, product or project-based. The AEC industry is mostly Project-Based. http://bit.ly/ielY3
			(Meso I)	**Is**	Sector 5	A sector is a "distinct subset of a market, society, industry, or economy whose components share similar characteristics" http://bit.ly/15UkZD
			(Micro I)	**Id**	Discipline 6	Disciplines are industry sectors, "branches of knowledge, systems of rules of conduct or methods of practice" http://bit.ly/7jT82
				Isp	Specialty 7	Specialty is a focus area of knowledge, expertise, production or service within a sub-discipline.
MESO Projects and their teams	**P**	Project Teams 8	n/a	**P**	Project Team 8	Project Teams are temporary groupings of organisations with the aim of fulfilling predefined objectives of a project - a planned endeavour, usually with a specific goal and accomplished in several steps or stages. http://bit.ly/dqMYg
MICRO Organisations, Units, their teams & members	**O**	Organisations 9	(Macro O)	**O**	Organisation 9	An organisation is a 'social arrangement which pursues collective goals, which controls its own performance, and which has a boundary separating it from its environment. http://bit.ly/v7p9N
			(Meso O)	**Ou**	Organisational Unit 10	Departments and Units are specialised divisions of an organisation. These can be co-located or distributed geographically.
				Ot	Organisational Team 11	Organisational Teams consist of a group of individuals (human resources) assigned to perform an activity or deliver a set of assigned objectives. Teams can be physically co-located or formed across geographical or departmental lines.
			(Micro O)	**Om**	Organisational Member 12	Organisational members can be part of multiple Organisational Teams.

4 BIM Maturity Index

The BIM Maturity Index[iv] (BIMMI) includes a set number of Maturity Levels which signify the evolutionary improvement of processes, technologies and policies within each BIM Stage. A maturity level is a "well-defined evolutionary plateau that institutionalizes new capabilities for developing the organization's workforce" (SEI, 2008g). Maturity levels allow for a basic distinction between *immature* and *mature* entities in terms of "systematic approach[es] to business processes" (Sarshar et al., 2000). With the exception of articles jestingly advocating multiple immaturity levels (Anthony, 1992), 'capability immaturity' or lack of maturity is typically identified as a fixed starting point. A collation of process maturity levels from 'immature' to 'highly mature' is typically referred to as a 'Maturity Model'.

Capability Maturity Models

The Capability Maturity Model (CMM) is a process improvement framework originally intended as a tool to evaluate the ability of government contractors to perform a software project. It was developed in the late 80s for the benefit of the US Department of Defence (Hutchinson & Finnemore, 1999). It's successor, the more comprehensive Capability Maturity Model Integration (CMMI), continues to be developed and extended by the Software Engineering Institute, Carnegie Mellon University. Below is a short historical synopsis of CMM, the basis for numerous maturity models across many industries:

> *"The U.S. Department of Defense (DoD) is the world's largest software customer, spending over $30 billion per year on software during the 1980s. At that time, software projects constantly seemed to be in crisis mode and were frequently responsible for large delays and overruns in defense systems. To address this software crisis on a national scale, the DoD funded the development of the Software Engineering Institute (SEI), a federally-funded research and development center (FFRDC), at Carnegie Mellon University in Pittsburgh, PA. Humphrey brought his process maturity concepts to the SEI in 1986, where he founded its Software Process Program. Shortly after arriving, he received a request from the U.S. Air Force to develop a method for assessing the capability of its software contractors"(SEI, 2008f).*

[iv] The author prefers to use the term BIM Maturity Index instead of BIM Maturity Model to minimise semantic confusion every time the word 'model' is invoked.

Capability Maturity Models originated in the field of quality management (Crosby, 1979) and are frameworks identifying a set of standardised process improvement levels which allow implementers to achieve significant business benefits. These include increased productivity and Return On Investment (ROI) as well as reduced costs and post-delivery defects (Hutchinson & Finnemore, 1999). Maturity models are typically made of multiple maturity levels; each level provides a layer in the foundation for continuous process improvement. Levels comprise of a set of process goals that, when satisfied, stabilise an important component in the 'construction' process. Achieving each level of the maturity framework establishes a different component" (Paulk, Weber, Garcia, Chrissis, & Bush, 1993).

Although CMM is not without its detractors (Weinberg, 1993) (Jones, 1994) (Bach, 1994), research conducted within other industries have already identified the correlation between improving process maturity and business performance (Lockamy III & McCormack, 2004). Researchers have argued that

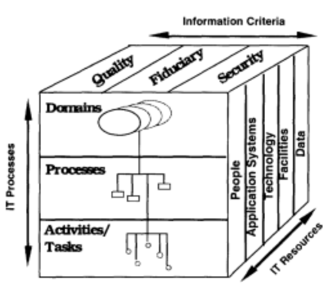
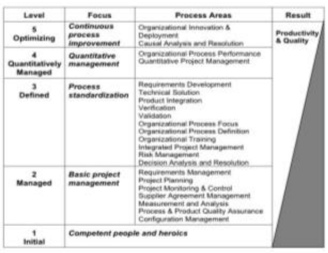
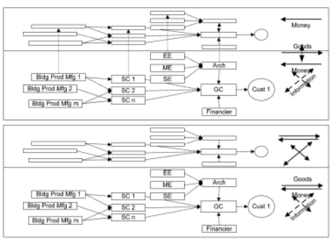
> *"to obtain consistently better results, it is (...) necessary to improve the process. For an organization to improve its capability, it is helpful to have a clear picture of the ultimate goal and a means to gauge progress along the way - hence the levels of the maturity model" (Jaco, 2004).*

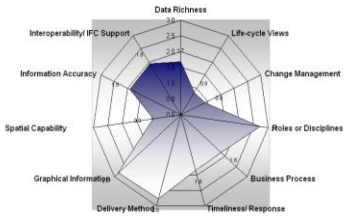
Currently available Capability Maturity Models are either specific to the software industry or focus mainly on the procedural aspects of an implementation process. The 'original' CMM is not applicable to the construction industry as it does not address supply chain issues and its maturity levels do not account for the different phases of a project lifecycle (Sarshar et al., 2000). Although there are a few (extensive) efforts which focus on the construction industry (refer to Table 5), there is no comprehensive maturity model/index that can be applied to BIM, its implementation stages, players, deliverables or its effect on project lifecycle phases.

Influences Shaping the BIM Maturity Index

It is important to benefit from existing maturity models/indices including those not intended specifically for the AECO industry. Many lessons can be learned and much experience can be gained by analysing, testing and then adopting some of the widely-used maturity terms, performance targets and quality assurance measures. Below are some of the published efforts that influenced the development of the BIM Maturity Index. Table 4 is a non-exhaustive list of source maturity models from different industries while Table 5 lists some of the widely adopted performance, excellence and quality management frameworks which influenced the BIM Maturity Matrix:

Table4. Maturity Models influencing the BIM Maturity Index

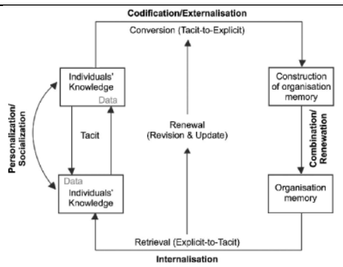
Sample Representation	**Abbreviation, Name** – *Organisation* Description and Number of maturity levels
	COBIT, Control Objects for Information and related Technology – *Information Systems Audit and Control Association (ISACA) and the IT Governance Institute (ITGI)*
 Image from (Lainhart IV, 2000)	The main objective of COBIT is to "enable the development of clear policy and good practice for IT control throughout organizations" (Lainhart IV, 2000). The COBIT Maturity Model is "an IT governance tool used to measure how well developed the management processes are with respect to internal controls. The maturity model allows an organization to grade itself from nonexistent (0) to optimized (5)" (Pederiva, 2003). COBIT includes 6 *Maturity Levels* (Non-existent, Initial/ad hoc, Repeatable but Intuitive, Defined Process, Managed and Measurable and Optimised), 4 *Domains* and 34 *Control Objectives*. Note: There is some alignment between ITIL (OGC, 2009) and COBIT with respect to IT governance within organisations (Sahibudin, Sharifi, & Ayat, 2008) of value to BIM implementation efforts.
	CMMI, Capability Maturity Model Integration - *Software Engineering Institute / Carnegie Melon*
 Image Source: NASA, Software Engineering Process Group http://bit.ly/CMMI-NASA	"Capability Maturity Model® Integration (CMMI) is a process improvement approach that (...) helps integrate traditionally separate organizational functions, set process improvement goals and priorities, provide guidance for quality processes, and provide a point of reference for appraising current processes" (SEI, 2006a) (SEI, 2006b) (SEI, 2008a) (SEI, 2008b) (SEI, 2008c). CMMI has 5 *Maturity Levels* (for Staged Representation, 6 Capability Levels for Continuous Representation), 16 core *Process Areas* (22 for CMMI-DEV and 24 for CMMI-SVC), 1 to 4 *Goals* for each Process Area, each goal is comprised of *Practices*... The 5 Maturity Levels are: Initial, Managed, Defined, Quantitatively Managed and Optimising.
 (Vaidyanathan & Howell, 2007)	**CSCMM, Construction Supply Chain Maturity Model** "Construction supply chain management (CSCM) refers to the management of information, flow, and money in the development of a construction project" as mentioned in (Vaidyanathan & Howell, 2007). CSCMM has 4 Maturity Stages: Ad-hoc, Defined, Managed and Controlled.



(Suermann, Issa, & McCuen, 2008)

I-CMM, **Interactive Capability Maturity Model** - *National Institute for Building Sciences (NIBS) Facility Information Council (FIC)*

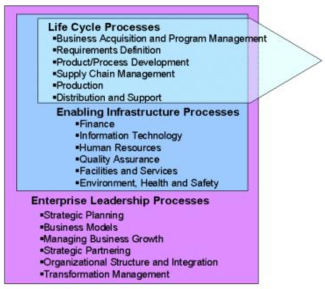
This I-CMM is closely coupled with the NBIMS effort (Version1, Part 1) and establishes "a tool to determine the level of maturity of an individual BIM as measured against a set of weighted criteria agreed to be desirable in a Building Information Model" (Suermann et al., 2008) (NIST, 2007) (NIBS, 2007). A more detailed discussion of this maturity model is offered in Section 4. The ICMM has 11 'Areas of Interest' measured against 10 Maturity Levels.



(Arif, Egbu, Alom, & Khalfan, 2009)

Knowledge Retention Maturity Levels

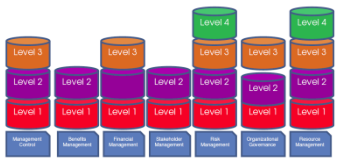
Arif, Egbu, Alom and Khalfan (2009) introduced 4 levels of knowledge retention maturity.
Knowledge management is an integral part of BIM capability and subsequent maturity. The Matrix thus incorporates these levels: (1) knowledge is shared between employees, (2) shared knowledge is documented (transferred from tacit to explicit), (3) documented knowledge is stored and (4) stored knowledge is accessible and easily retrievable (Arif et al., 2009).



(Nightingale & Mize, 2002)

LESAT, **Lean Enterprise Self-Assessment Tool** - *Lean Aerospace Initiative (LAI) at the Massachusetts Institute of Technology (MIT)*

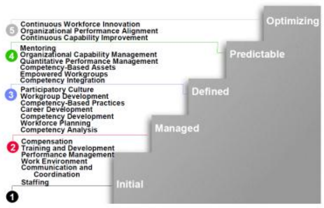
LESAT is focused on "assessing the degree of maturity of an enterprise in its use of 'lean' principles and practices to achieve the best value for the enterprise and its stakeholders" (Nightingale & Mize, 2002).
LESAT has 54 Lean Practices organised within three Assessment Sections: Lean Transformation/ Leadership, Life Cycle Processes and Enabling Infrastructure *and* 5 Maturity Levels: Some Awareness/Sporadic, General Awareness/Informal, Systemic Approach, Ongoing Refinement and Exceptional/Innovative.



(OGC, 2008)

P3M3, **Portfolio, Programme and Project Management Maturity Model** - *Office of Government Commerce*

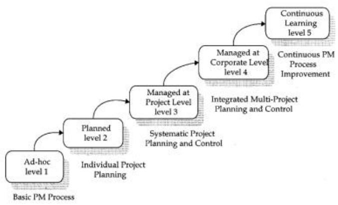
The P3M3 provides "a framework with which organizations can assess their current performance and put in place improvement plans with measurable outcomes based on industry best practice" (OGC, 2008).
The P3M3 has 5 Maturity Levels: Awareness, Repeatable, Defined, Managed and Optimised.



(SEI, 2008g)

P-CMM®, **People Capability Maturity Model** v2 – *Software Engineering Institute / Carnegie Melon*

P-CMM is an "organizational change model" and a "roadmap for implementing workforce practices that continuously improve the capability of an organization's workforce" (SEI, 2008g).
P-CMM has 5 Maturity Levels: Initial, Managed, Defined, Predictable and Optimising.



(Kwak & Ibbs, 2002)

(PM)², Project Management Process Maturity Model

The project management process maturity (PM)² model "determines and positions an organization's relative project management level with other organizations". It also aims to integrate PM "practices, processes, and maturity models to improve PM effectiveness in the organization" (Kwak & Ibbs, 2002).
(PM)² has 5 Maturity Levels: Initial, Planned, Managed at Project Level, Managed at Corporate Level and Continuous Learning.

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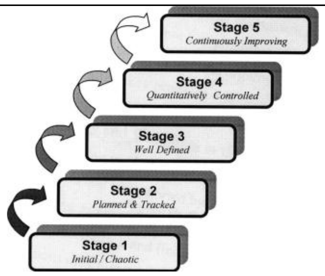
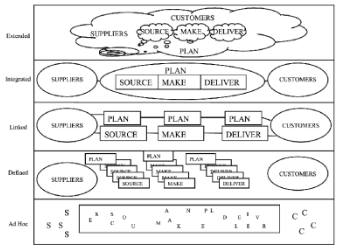
<td rowspan="2">

(Hutchinson & Finnemore, 1999)</td>
<td>SPICE, Standardised Process Improvement for Construction Enterprises - Research Centre for the Built and Human Environment, The University of Salford</td>
</tr>
<tr>
<td>SPICE is a project which developed a framework for continuous process improvement for the construction industry. SPICE is an “evolutionary step-wise model utilizing experience from other sectors, such as manufacturing and IT” (Hutchinson & Finnemore, 1999), (Sarshar et al., 2000).
SPICE has 5 Stages: Initial/Chaotic, Planned & Tracked, Well Defined, Quantitatively Controlled, and Continuously Improving.</td>
</tr>
<tr>
<td rowspan="2">

(Lockamy III & McCormack, 2004)</td>
<td>Supply Chain Management Process Maturity Model and Business Process Orientation (BPO) Maturity Model</td>
</tr>
<tr>
<td>The model conceptualizes the relation between process maturity and supply chain operations as based on the Supply-chain Operations Reference Model[v] (Stephens, 2001). The model’s maturity describes the “progression of activities toward effective SCM and process maturity. Each level contains characteristics associated with process maturity such as predictability, capability, control, effectiveness and efficiency" (Lockamy III & McCormack, 2004) (K. McCormack, 2001).
The 5 Maturity Levels are: Ad-hoc, Defined, Linked, Integrated and Extended.</td>
</tr>
<tr>
<td colspan="2">Other maturity models – or variation on listed maturity models - include those on Software Process Improvement (Hardgrave & Armstrong, 2005), IS/ICT Management Capability (Jaco, 2004), Project Management (Crawford, 2006), Competency (Gillies & Howard, 2003) and Financial Management (Doss, Chen, & Holland, 2008).</td>
</tr>
</table>

The above listed Capability Maturity Models are similar in structure and objectives but differ in conceptual depth, industrial focus, terminology and target audience. A common theme is how Capability Maturity Models employ few simple experience–based classifications and benchmarks to facilitate continuous improvement within organisations.

In analysing their suitability for the development of a BIM-specific maturity index, most were broad in approach and can collectively form a basis for a range of BIM processes, technologies and policies. However, none of the models surveyed were easily scalable across the twelve organisational scales (identified in Table 3). Also, from a terminology standpoint, there are not enough differentiation between the notion of *capability* (the ability to perform a task) and that of *maturity*[vi] (degrees of excellence in performing a task). This differentiation, in the author’s view, is critical to cater for staged BIM implementation mandated by its disruptive and expansive nature.

It is also important to *not only* (i) identify BIM-specific maturity benchmarks, but to (ii) identify the detailed procedures to achieve these benchmarks and to (iii) develop a suitable scoring system for measuring teams and organisations against them. To attain all these objectives, the BIM Maturity Matrix – a performance improvement tool introduced in Section 5 – tries to learn from numerous Business Performance, Excellence and Quality Management models (Table 5):

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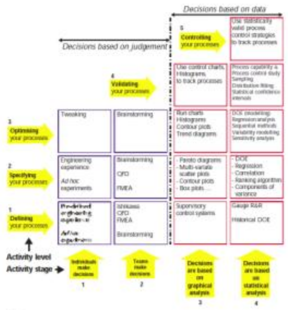
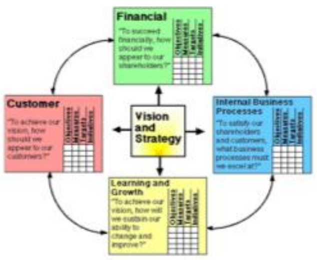
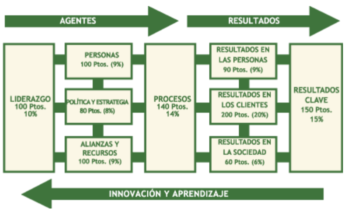
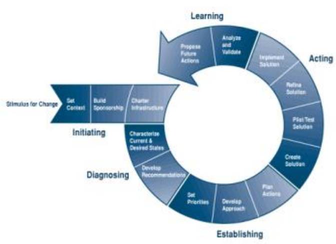
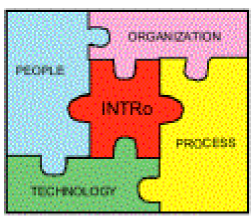
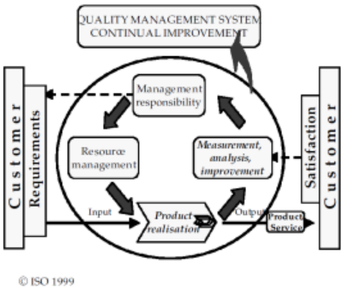
[v] For an overview of the latest Supply-chain Operations Reference Model (SCOR), version 9, please refer to http://bit.ly/SCORv9.

[vi] Please note that the terms Capability and Maturity are used differently by the Software Engineering Institute – Carnegie Melon, to denote CMMI “Continued Representation” and “Staged Representation” respectively.

Table 5. Performance, Excellence and Quality Management frameworks influencing the BIM Maturity Matrix

Sample Representation	**Abbreviation, Name** – *Organisation* Description and *specific influence on the BIM Maturity Matrix*
 Image from (NIST, 2008)	**Baldrige National Quality Program**, 2008 Criteria for Performance Excellence - *US Department of Commerce and National Institute of Standards and Technology (NIST)* The Malcolm Baldrige Quality Award is an overall performance award conducted by evaluating/scoring organisations against 7 Categories of Performance (using a 1000 points scale): Leadership, Strategic Planning, Customer/Market Focus, Information & Analysis, Human Resource Focus, Process Management, and Business Results (NIST, 2008). *Note: BIM Capability and Maturity assessment tools partially introduced in this chapter are influenced by Baldrige's "quality of documented processes" as well as its scoring system.*
 Link: http://bit.ly/Scorecard	**BSC**, **The Balanced Scorecard** The Balanced Scorecard is a performance management tool (Kaplan & Norton, 1996a) and a strategic management system (Kaplan & Norton, 1996b). BSC has 4 Perspectives: Learning and Growth, Business Process, Customer and Financial Perspectives. Using the Balanced Scorecard within the industry has been discussed in the Conceptual Framework for Performance Management in Construction (Kagioglou, Cooper, & Aouad, 2001). *Note: BIm³ and other BIM performance measurement tools benefited from BSC's approach in clarifying how organisations align overall BIM strategy with other organisational objectives.*
 Link: http://bit.ly/EFQMem	**EFQM Excellence Model** - *European Foundation for Quality Management* The EFQM (EFQM, 2008) Excellence Model is an annual award which includes 9 Concepts: Leadership, Policy & Strategy, People, Partnerships & Resources, Processes, Customer Results, People Results, Society Results and Key Performance Areas. Organisations may be assessed against, at least, 3 organisational maturity levels. *Note: BIM performance measurement tools can specifically benefit from EFQM and its applicability within the construction industry (Watson & Seng, 2001)*
 Link: http://bit.ly/IDEAL	**IDEAL**, **Initiating, Diagnosing, Establishing, Acting & Learning Model** – *Software Engineering Institute / Carnegie Melon* "The IDEAL model is an organizational improvement model that serves as a roadmap for initiating, planning, and implementing improvement actions". It has 5 Phases: Initiating, Diagnosing, Establishing, Acting and Learning (SEI, 2008d). *Note: The BIm³ - which includes BIM Stages and Steps as two of its components – is indirectly influenced by the IDEAL model.*
 Link: http://bit.ly/INTRO-SEI	**INTRo**, **IDEAL-based Based New Technology Rollout** - *Software Engineering Institute / Carnegie Melon* INTRo embodies "detailed how-to information needed to manage the introduction of a new technology, organized into a work breakdown structure of stages, steps, and tasks. Tips, checklists, guidelines, and tutorials accompany process descriptions". It has 7 Stages of new technology implementation: Project Initiation, Organizational Analysis, Technology-Based Solution Definition, Technology Selection and Testing, Whole Product Design, Breakthrough and Rollout (Levine, 2000) (SEI, 2008e). *Note: BIM Capability and Maturity assessments, introduced partially in this chapter, benefited from INTRo's subdivisions. This is more apparent in low-granularity BIM Competency Areas.*



© ISO 1999, (Russell, 2000)

ISO 9000 Quality Management System - *The International Organization for Standardization*

The basic model of ISO 9000 includes 8 Principles (ISO, 2008a) (ISO, 2008b) which align somewhat with EFQM (Russell, 2000). ISO 9001 includes 20 clauses meant for services organisations (Jalote, 2000) and can be mapped and compared against the CMM (Paulk, 1994).

Note: BIm³ did not directly borrow from ISO standards but attempted to avoid any irresolvable clashes with its principles and terminology.

PD Prime Designer
DC Design Consultants
PC Prime Constructor
TC Trade Contractors
S Suppliers

Level of Detail (LOD) and Model Component Author (MCA)

Conceptual-ization		Criteria Design		Detailed Design		Implemen-tation Docs	
LOD	MCA	LOD	MCA	LOD	MCA	LOD	MCA
100	PD	200	DC	300	TC	400	TC
100	PD	100	DC	300	TC	400	TC
100	PD	200	DC	300	TC	400	TC

(AIA, 2008)

MPS, **Model Progression Specification** for Building Information, Integrated Project Delivery Models - *American Institute of Architects*

The MPS (AIA, 2008) is beneficial in establishing the optimum amount of details needed within a building information model at each project lifecycle phase and sub-phase. From a process improvement perspective, an organisation or a project team - implementing BIM with a degree of performance maturity - will need to establish its optimum Level of Detail to minimise *under* and/or *over* representation. The MPS has 5 Levels of Detail (LOD) measured against 4 Model Component Authors (MCA).

Note: BIm³ and other BIM Capability/Maturity tools incorporate LODs and MCAs as part of their assessments.

Other models of relevance and of potential benefit to BIm³ and other BIM Capability/Maturity assessment tools include: **ISO/IEC 15504**, **Information Technology - Process Assessment** Part 4: Guidance on use for process improvement and process capability determination - *International Standards Organisation* (ISO, 2004) and **ITIL**, **Information Technology Infrastructure Library** - *Office of Government Commerce (OGC) in UK* (OGC, 2009) (Cartlidge et al., 2007).

The above frameworks form a good basis to generate a comprehensive scoring system for measuring BIM Capability and Maturity. They will also guide the preparation of multiple knowledge tools tailored to assist industry stakeholders in *implementing* and *assessing* BIM in a systematic and repeatable fashion.

Focus on NBIMS Capability Maturity Model

Before introducing a new maturity index, it is important to properly evaluate existing BIM-specific maturity models. At the time this chapter was readied for publication, two efforts where publically available: the NBIMS' I-CMM and Indiana University's BIM Proficiency Matrix[vii]. Since not enough documentation - relating to Indiana University's effort - were located, this Section will exclusively focus on NBIMS' approach to BIM maturity assessment and reporting:

The U.S. National Building Information Model Standard™ "establishes standard definitions for building information exchanges to support critical business contexts using standard semantics and ontologies…[to be]…implemented in software". NBIM Standard Version 1 – Part 1 proposes a Capability Maturity Model (CMM) for "users to evaluate their business practices along a continuum or spectrum of desired technical level functionality" and "for use in measuring the degree to which a building information model implements a mature BIM Standard" (NIST, 2007).
There are two versions of NBIMS' CMM. The first is a static tabular version identifying eleven 'Areas of Interest' measured against ten Levels of increasing maturity (Figure 8). The second is the Interactive Capability Maturity Model (I-CMM), a multi-tab Microsoft Excel® workbook based on the static tabular model (NIBS, 2007). The I-CMM is intended for use as an 'internal tool' (internal to organisations) deployed to "determine the level of maturity of an individual BIM [project] as measured against a set of weighted criteria agreed to be desirable in a Building Information Model" (NIST, 2007) (Suermann et al., 2008). I-CMM focuses primarily on measuring BIM information management and "should not be used as a benchmark for any other metrics" including those related to architectural, engineering, construction and management. It is also not intended as a "tool to compare BIMs or BIM implementations" (NIST, 2007).

[vii] Indiana University BIM Proficiency Matrix includes eight categories measured against four maturity/proficiency levels. The matrix focuses on the accuracy and richness of the digital model (as an end-product) and has less focus on the process of creating that digital model. More information is available at http://bit.ly/iuBIM (last updated 28.10.2009, last checked 04.11.2009).

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

© NIBS 2007

Figure 8. NBIMS CMM Chart (adopted from NIBS, 2007) – more readable MS Excel chart at http://bit.ly/NBIMS

NBIMS' I-CMM is based on the concept of Minimum BIM: achieving a minimum total score for maturity across 'Areas of Interest' beyond which a project is not considered 'true BIM'.

NBIM Standard, version 1 states that "one should obtain a minimum score of 20.1 in order to consider true BIM maturity". It is however noted that the minimum score for the distinction of a 'Minimum BIM' is not fixed but is "dependent on the date the interface [the I-CMM tool] is used". The minimum score thus changes[viii] yearly or "as the rhetorical bar is raised and owners demand more from the models being delivered" (NIST, 2007). Also, each of the 11 Areas of Interest used in NBIMS' CMM are weighted. This weighting scheme is not conceptually fixed but can be preferentially altered by organisations as they see fit.
NBIMS' CMM is still in its early days of development (NIST, 2007) and may yet change significantly. However, in its current form, NBIMS's CMM and the I-CMM tool suffer from structural limitations that may restrict its usefulness and usability:

- NBMIS' CMM employs ten maturity levels with minimal distinction between them. Most capability maturity models surveyed - from within and outside the AECO industry - include only four, five or six distinctive levels (refer to Table 6).
- The Areas of Interest used are not easily understood and may significantly overlap (Suermann et al., 2008) (McCuen, 2007). This may still be true even with the additional explanatory tab available within the I-CMM tool.

[viii] The minimum score changed to 30 in June, 2009 and then became 40 soon after that (last I-CMM tool checked was v1.9 - August 24, 2009).

- The variability of the ‘minimum score for the Minimum BIM’ will cause scoring inconsistencies. Pre-assigning the minimum score according to calendar year _and_ allowing it to be changed ‘according to demands by owners’ are in sharp contrast. Also, it is difficult to imagine that industry’s BIM maturity will increase (or can be encouraged to increase) in a pre-defined linear fashion or that owners’ BIM requirements can be established/ represented through a generic minimum score.
- The variability of scoring-weights assigned to Areas of Interest in accordance to organisational preference (or the elusive ‘national consensus’) – as encouraged within the NBIM Standard - will minimise the usefulness of the I-CMM tool and neutralise the ‘certification’ process.
- The current configuration of the I-CMM tool allows organisations/projects to accumulate high total scores even if they achieved very low scores on a number of Areas of Interest (‘platinum’ certification can be achieved even when a project has no Change Management or Spatial Capability).
- The NBIM’s CMM Areas of Interest are only useful in assessing Models and not the teams, organisations or project-teams which generate them.
- The NBIM’s CMM in both its static and dynamic versions can only be applied ‘internally’ through self-assessment or peer-revision.
- Most importantly, the inability of the NBIM’s CMM – in its current form - to assess any BIM metric beyond ‘information management’ (NIST, 2007) severely limits its applicability and usefulness.

The AECO industry, challenged by the widely-reported capabilities and requirements of Building Information Modelling, will benefit from the availability of a maturity index that can assess a host of metrics across many organisational scales. The availability of such a BIM-specific maturity index will assist individuals, organisations and industry bodies to (a) justify investment in BIM competency development and productivity enhancement, (b) asses their BIM performance, strengths and weaknesses and (c) potentially gain market recognition for their BIM products and service quality.

BIM-specific Maturity Index

A BIM-specific maturity index has been developed by analysing then integrating several models from different industries. Its Maturity Levels reflect the *extent* of BIM abilities, deliverables and their requirements as opposed to *minimum* abilities reflected through Capability Stages. The BIM Maturity Index has five distinct levels: (a) Initial/ Ad-hoc, (b) Defined, (c) Managed, (d) Integrated and (e) Optimised. Level names have been chosen through comparing terminology used by many maturity models (Table 6) followed by selecting those easily understandable by AECO stakeholders and able to reflect the increasing BIM maturity from ad-hoc to continuous improvement.

Table 6. A non-exhaustive list of terminology used by CMMs to denote maturity levels including those used by the BIM Maturity Index

MATURITY LEVELS

Maturity Models	**0**	**1** *or* **a**	**2** *or* **b**	**3** *or* **c**	**4** *or* **d**	**5** *or* **e**
BIM Maturity Index		Initial/ Ad-hoc	Defined	Managed	Integrated	Optimised
COBIT, Control Objects for Information and related Technology	Non-existent	Initial/ Ad- hoc	Repeatable but Intuitive	Defined Process	Managed & Measurable	Optimised
CMMI, Capability Maturity Model Integration (Staged Representation)		Initial	Managed	Defined	Quantitatively Managed	Optimising
CMMI (Continuous Representation)	Incomplete	Performed	Managed	Defined	Quantitatively Managed	Optimising
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	Optimising
P3M3, Portfolio, Programme and Project Management Maturity Model		Awareness	Repeatable	Defined	Managed	Optimised
$(PM)^2$, Project Management Process Maturity Model		Ad-hoc	Planned	Managed at Project Level	Managed at Corporate Level	Continuous Learning
SPICE, Standardised 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

In general, the progression from low to higher levels of maturity indicate (i) better control through minimising variations between targets and actual results, (ii) better predictability and forecasting by lowering variability in competency, performance and costs *and* (iii) greater effectiveness in reaching defined goals and setting new more ambitious ones (Lockamy III & McCormack, 2004) (Kevin McCormack, Ladeira, & Oliveira, 2008). In this chapter, it will be difficult to discuss all maturity levels pertaining to all capability stages at all organisational scales. Only one sample capability/maturity/scale combination will be generically described below. Descriptions of other maturity combinations can be gleaned from Table 4.

The following is a hypothetical assessment report for an Organisation (organisational scale 9) discovered to be at Capability Stage 1 (object-based modelling) and Maturity Level a (initial/ad-hoc):

> *Summary:* the organisation is at Capability Stage 1 with Maturity Level 'a'. BIM implementation is characterised by *the absence of* an overall strategy and *a significant shortage of* defined processes and policies. BIM software tools are deployed in a non-systematic fashion and without adequate prior investigations and preparations. BIM adoption is only partially achieved through the 'heroic' efforts of individual champions – a process that lacks the active and consistent support of middle and senior management.
>
> *Technology:* Usage of software applications is unmonitored and unregulated. Software licence numbers are typically misaligned to staff requirements. 3D Models are relied upon to mainly generate accurate 2D representations/deliverables. Data usage and storage are not well defined and data exchanges suffer from a severe lack of interoperability.
> Hardware specifications are non-uniform and fall well-below staff skills and expected BIM deliverables. Equipment replacement and upgrades are treated as cost items, postponed whenever possible and committed to only when unavoidable.
> Network solutions are non-existent or ad-hoc. Individuals and teams use whatever tools available to communicate and share data. Stakeholders lack the network infrastructure necessary to harvest, store and share knowledge.
>
> *Process:* Senior leaders/managers have varied visions about BIM and its implementation is conducted without an overall strategy. As typical at this maturity level, BIM is treated as a technology stream without much consideration for its process and policy implications. Change resistance is evident among staff and possibly wide-spread amongst middle management.
> The workplace environment is not recognised as a factor in staff satisfaction/motivation and is not conducive to productivity. Knowledge is not recognised as an organisational asset and is mainly shared informally between staff - through tips, techniques and lessons learned.
> Business opportunities arising from BIM are not acknowledged. BIM objects (components, parts or families) are not consistently available in adequate numbers or quality. 3D models deliverables (as BIM products) suffer from too high, too low or inconsistent levels of detail. More importance is given to visual quality of 2D representations than is given to 3D model accuracy.
> Products and services offered by the organisation represent a fraction of the capabilities inherent within the software tools employed. There are no modelling quality checks or formal audit procedures.

BIM Projects are conducted using inconsistent practices and there are no project initiation or closure protocols. Staff competency levels are unknown to management, roles are ambiguous and team structures pre-date BIM. Staff are neither structurally trained nor inducted into BIM processes; are generally confused about workflows and 'who to go to' for technical and procedural assistance.
Performance is unpredictable and productivity depends on champions' efforts within teams. A mentality of 'shortcuts' and 'working around the system' flourishes. Performance is inconsistent and is neither monitored nor reported in any systematic fashion. In general, islands of concentrated BIM productivity are separated by seas of BIM idleness/confusion.

Policy: The organisation does not document or adopt BIM-specific guidelines and standards. There are minor or inconsistent quality controls for 3D models and 2D representation. There are no training policies, and educational mediums – when available - are not suitable or accessible to staff. Contractually, there is a dependence on pre-BIM arrangements with no BIM-specific risk identification and mitigation policies.

The above is a generic summary-description of a hypothetical organisation grappling with low BIM maturity while implementing object-based modelling. The BIM Maturity Matrix (BIm^3), introduced in the next section, is a comprehensive knowledge tool that assists individuals, organisations and other organisational scales in planning, achieving and assessing BIM performance milestones.

5 The BIM Maturity Matrix

The BIM Maturity Matrix (BIm³) is a knowledge tool which incorporates many BIM Framework components for the purpose of performance measurement and improvement. Both its structure and content have benefited from time-tested maturity (Table 4) and excellence models (Table 5). To enable its wide applicability across the AECO industry, the BIM Maturity Matrix follows a set of guiding principles. BIm³ has been developed to be:

- *Specific:* the Matrix is composed of a set of interlocking BIM capability stages, steps, organisational scales, maturity areas and levels. All components are well defined, complementary and serve specific purposes in assessing BIM capability and maturity.
- *Attainable:* all BIM capability stages and maturity levels can be achieved through an accumulation of defined actions.
- *Applicable:* the Maturity Matrix can be equally utilised by all AECO stakeholders across all Project Lifecycle Phases.
- *Flexible*: capability and maturity assessments can be performed across organisational scales.
- *Gradual:* the Matrix reflects and encourages smooth progression to increasingly higher capability and/or maturity.
- *Cumulative:* BIM capability stages and maturity levels, the two main components of the Matrix, are logical progressions. Deliverables from one capability stage or maturity level are prerequisites for the next stage or level.
- *Current:* the Matrix is designed around current and emerging technologies. Also, its format, dependencies and terminology have been selected to minimise the need for frequent structural changes.
- *Informative:* The Matrix provides "feedback for improvement" as well as "guidance for next steps" (Nightingale & Mize, 2002).
- *Measurable:* maturity assessments are linked to capability stages and organisational scales. This allows like-to-like comparisons without compromising units of measurement.
- *Granular:* maturity assessments can be conducted at multiple granularity levels, delivering a stepped-range of scores and reports.
- *Neutral:* the BIM Maturity Matrix does not prejudice proprietary, non-proprietary, closed, open, free or commercial solutions/ schemas. It can be employed by stakeholders irrespective of their technical persuasion.
- *Relevant:* the Matrix and its underlying concepts are relevant to both industry and academia; this should encourage its adoption and development respectively.

To meet the above guiding principles, the BIM Maturity Matrix combines several BIM Framework components represented in Figure 9 below:

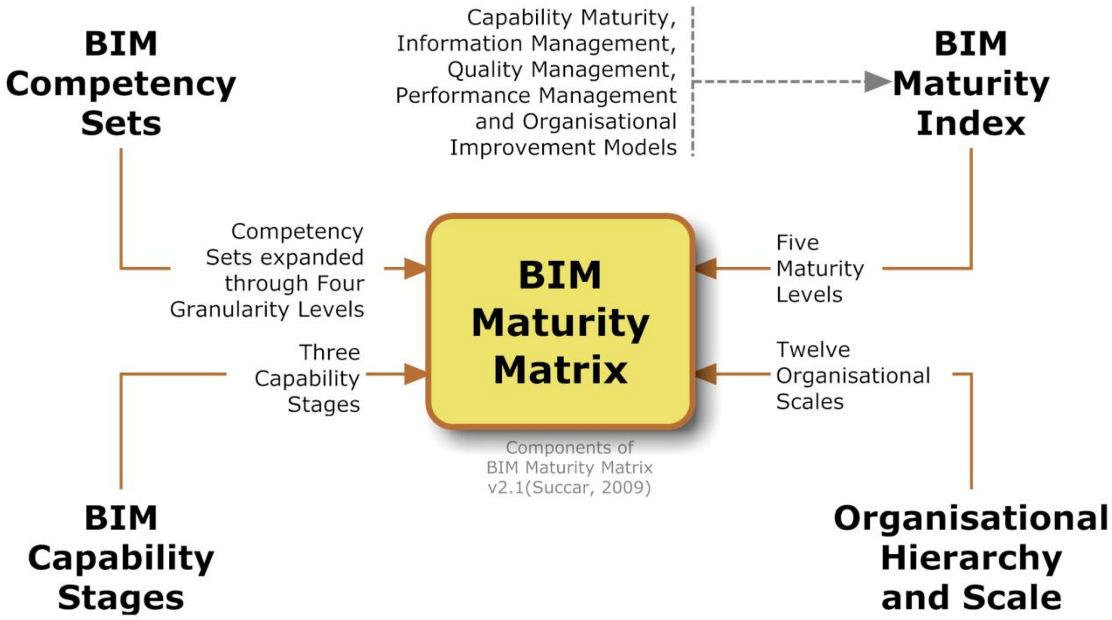


Figure 9. Components of the BIM Maturity Matrix v2.2

Sample Static Tabular Form

The BIM Maturity Matrix incorporates a set of concepts whose interactions can be represented through many static and dynamic mediums. The Matrix, in its expanded database-driven form, includes all Capability Stages, Maturity Levels and Organisational Scales.

Table 7 below introduces a static representation of the Matrix at a sample Granularity Level:

BIM MATURITY MATRIX

BIM COMPETENCY SETS		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.

BIM COMPETENCY SETS		BIM Competency Areas at Granularity level 1	a INITIAL	b DEFINED	c MANAGED	d INTEGRATED	e OPTIMISED
	PROCESS	**Infrastructure:** physical and knowledge-related	The work environment is either not recognised as a factor in staff satisfaction or may not be conducive to productivity. Knowledge is not recognised as an asset; BIM knowledge is typically shared informally between staff (through tips, techniques and lessons learned).	The work environment and workplace tools are identified as factors affecting motivation and productivity. Similarly, knowledge is recognised as an asset; shared knowledge is harvested, documented and thus transferred from tacit to explicit.	The work environment is controlled, modified and it's criteria managed to enhance staff motivation, satisfaction and productivity. Also, documented knowledge is adequately stored.	Environmental factors are integrated into performance strategies. Knowledge is integrated into organisational systems; stored knowledge is made accessible and easily retrievable [refer to the 4 levels of knowledge retention (Arif et al., 2009)].	Physical workplace factors are reviewed constantly to insure staff satisfaction and an environment conducive to productivity. Similarly, knowledge structures responsible for acquisition, representation and dissemination are systematically reviewed and enhanced.
		Products & Services specification, differentiation, project delivery approach and R&D	3D models deliverables (a BIM product) suffer from too high, too low or inconsistent levels of detail.	A "statement defining the object breakdown of the 3D model" (Bouygues, 2007) is available.	Adoption of product/ service specifications similar to Model Progression Specifications (AIA, 2008), BIPS 'information levels' (BIPS, 2008) or similar.	Products and services are specified and differentiated according to Model Progression Specifications or similar.	BIM products and services are constantly evaluated; feedback loops promote continuous improvement.
		Human Resources: competencies, roles, experience and dynamics	There is an absence of defined processes; roles are ambiguous and team structures/dynamics are inconsistent. Performance is unpredictable and productivity depends on individual heroics. A mentality of 'working 'around the system' flourishes.	BIM roles are informally defined and teams are formed accordingly. Each BIM project is planned independently. BIM competency is identified and targeted; BIM heroism fades as competency increases but productivity is still unpredictable.	Cooperation within organisations increases as tools for cross-project communication are made available. Flow of information steadies; BIM roles are visible and targets are achieved more consistently.	BIM roles and competency targets are imbedded within the organisation. Traditional teams are replaced by BIM-oriented ones as new processes become part of organisation's / project team's culture. Productivity is now consistent and predictable.	BIM competency targets are continuously upgraded to match technological advances and align with organisational objectives. Human resource practices are proactively reviewed to insure intellectual capital matches process needs.
		Leadership: innovation and renewal, strategic, organisational, communicative and managerial attributes	Senior leaders/ managers have varied visions about BIM. BIM implementation (according to BIM Stage requirements) is conducted without a guiding strategy. At this maturity level, BIM is treated as a technology stream; innovation is not recognised as a independent value and business opportunities arising from BIM are not acknowledged.	Senior leaders/managers adopt a common vision about BIM. BIM implementation strategy lacks actionable details. BIM is treated as a process-changing, technology stream. Product and process innovations are recognised; business opportunities arising from BIM are identified but not exploited.	The vision to implement BIM is communicated and understood by most staff. BIM implementation strategy is coupled with detailed action plans and a monitoring regime. BIM is acknowledged as a series of technology, process and policy changes which need to be managed without hampering innovation. Business opportunities arising from BIM are acknowledged and used in marketing efforts.	The vision is shared by staff across the organisation and/or project partners. BIM implementation, its requirements and process/ product innovation are integrated into organisational, strategic, managerial and communicative channels. Business opportunities arising from BIM are part of team, organisation or project-team's competitive advantage and are used to attract and keep clients.	Stakeholders have internalised the BIM vision and are actively achieving it (Nightingale & Mize, 2002). BIM implementation strategy and its effects on organisational models are continuously revisited and realigned with other strategies. If alterations are needed, they are proactively implemented. Innovative product/ process solutions and business opportunities are sought-after and followed through relentlessly.

BIM COMPETENCY SETS		BIM Competency Areas at Granularity level 1	a INITIAL	b DEFINED	c MANAGED	d INTEGRATED	e OPTIMISED
	POLICY	**Regulatory**: rules/ directives, standards/ classifications, guidelines/ benchmarks and codes/ regulations	There are no BIM guidelines, documentation protocols or modelling standards. There is an absence of documentation and modelling standards. There is informal or no quality control plans; neither for 3D models nor for documentation. There are no performance benchmarks for processes, products or services.	Basic BIM guidelines are available (e.g. training manual and BIM delivery standards). Modelling and documentation standards are well defined according to market-accepted standards. Quality targets and performance benchmarks are set.	Detailed BIM guidelines are available (training, standards, workflow, exceptions...). Modelling, representation, quantification, specifications and analytical properties of 3D models are managed through detailed modelling standards and quality plans. Performance against benchmarks is tightly monitored and controlled.	BIM guidelines are integrated into overall policies and business strategies. BIM standards and performance benchmarks are incorporated into quality management and performance improvement systems.	BIM guidelines are continuously and proactively refined to reflect lessons learned and industry best practices. Quality improvement and adherence to regulations and codes are continuously aligned and refined. Benchmarks are repetitively revisited to insure highest possible quality in processes, products and services
		Contractual: responsibilities, rewards and risks	Dependence on pre-BIM contractual arrangements. BIM risks related to model-based collaboration (differ in each market) are not recognised or are ignored.	BIM requirements are recognised. “Statements defining the responsibility of each stakeholder regarding information management” (Bouygues, 2007) are now available.	There is a mechanism to manage shared BIM intellectual property, confidentiality, liability and a system for BIM conflict resolution.	Organisation are aligned through trust and mutual dependency beyond contractual barriers.	Responsibilities, risks and rewards are continuously revisited and realigned to effort. Contractual model are modified to achieve best practices and highest value for all stakeholders.
		Preparatory: research efforts/ deliverables, educational programmes/ deliverables and training programmes	Very little or no training available to BIM staff. Educational/ training mediums are not suitable to achieve the results sought.	Training requirements are defined and are typically provided only when needed. Training mediums are varied allowing flexibility in content delivery.	Training requirements are managed to adhere to pre-set broad competency and performance objectives. Training mediums are tailored to suit trainees and reach learning objectives in a cost-effective manner.	Training is integrated into organisational strategies and performance targets. Training is typically based on staff roles and respective competency objectives. Training mediums are incorporated into knowledge and communication channels.	Training is continuously evaluated and improved upon. Training availability and delivery methods are tailored to allow multi-modal continuous learning.

			a	b	c	d	e
			INITIAL	**DEFINED**	**MANAGED**	**INTEGRATED**	**OPTIMISED**
BIM CAPABILTY STGAES	**STAGE 1**	**Object-based Modelling**: single-disciplinary use within a Project Lifecycle Phase	Implementation of an object-based tool. No process or policy changes identified to accompany this implementation.	Pilot projects are concluded. BIM process and policy requirements are identified. Implementation strategy and detailed plans are prepared.	BIM processes and policies are instigated, standardised and controlled.	BIM technologies, processes and policies are integrated into organisational strategies and aligned with business objectives.	BIM technologies, processes and policies are continuously revisited to benefit from innovation and achieve higher performance targets.
	STAGE 2	**Modelling-based Collaboration**: multi-disciplinary, fast-tracked interchange of models	Ad-hoc BIM collaboration; in-house collaboration capabilities incompatible with project partners. Trust and respect between project participants may be lacking.	Single-thread, well-defined yet reactive BIM collaboration. There are identifiable signs of mutual trust and respect among project participants.	Multi-thread proactive collaboration; protocols are well documented and managed. There are mutual trust, respect and sharing of risks and rewards among project participants.	Multi-thread collaboration includes downstream players. This is characterised by the involvement of key participants during projects' early lifecycle phases.	Multi-thread team included all key players in an environment characterised by goodwill, trust and respect.
	STAGE 3	**Network-based Integration**: concurrent interdisciplinary interchange of nD models across Project Lifecycle Phases	Integrated models are generated by a limited set of project stakeholders - possibly behind corporate firewalls. Integration occurs with little or no pre-defined process guides, standards or interchange protocols. There is no formal resolution of stakeholders' roles and responsibilities.	Integrated models are generated by a large subset of project stakeholders. Integration follows predefined process guides, standards and interchange protocols. Responsibilities are distributed and risks are mitigated through contractual means.	Integrated models (or parts of) are generated and managed by most project stakeholders. Responsibilities are clear within temporary project alliances or longer-term partnerships. Risks and rewards are actively managed and distributed.	Integrated models are generated and managed by all key project stakeholders. Network-based integration is the norm and focus is no longer on *how* to integrate models/ workflows but on proactively detecting and resolving technology, process and policy misalignments.	Integration of models and workflows are continuously revisited and optimised. New efficiencies, deliverables and alignments are actively pursued by a tightly-knit interdisciplinary project team. Integrated models are contributed to by many stakeholders along the construction supply chain.
ORGANISATIONAL SCALES	**MICRO**	**Organisations:** dynamics and BIM deliverables	BIM leadership is non-existent; implementation depends on technology champions.	BIM leadership is formalised; different roles within the implementation process are defined.	Pre-defined BIM roles complement each other in managing the implementation process.	BIM roles are integrated into organisation's leadership structures.	BIM leadership continuously mutates to allow for new technologies, processes and deliverables.
	MESO	**Project Teams** (multiple organisations): inter-organisational dynamics and BIM deliverables	Each project is run independently. There is no agreement between stakeholders to collaborate beyond their current common project.	Stakeholders think beyond a single project. Collaboration protocols between project stakeholders are defined and documented.	Collaboration between multiple organisations over several projects is managed through temporary alliances between stakeholders.	Collaborative projects are undertaken by inter-disciplinary organisations or multidisciplinary project teams; an alliance of many key stakeholders.	Collaborative projects are undertaken by self-optimising interdisciplinary project teams which include most stakeholders.
	MACRO	**Markets:** dynamics and BIM deliverables	Very few supplier-generated BIM components (virtual products and materials representing physical ones). Most components are prepared by software developers and end-users.	Supplier-generated BIM components are increasingly available as manufactures/ suppliers identify the business benefits.	BIM Components are available through highly accessible/searchable central repositories. Components are not interactively connected to suppliers' databases.	Access to component repositories is integrated into BIM software. Components are interactively linked to source databases (for price, availability, etc...).	Dynamic, multi-way generation and interchange of BIM components (virtual products and materials) between all project stakeholders through central or meshed repositories.

Table 7. Building Information Modelling Maturity Matrix – static tabular guide at sample granularity, v1.1

6 Granularity of Competency Sets and Areas

Competency Sets include a large number of individual competencies grouped under numerous competency headings (refer to Figure 5). To enhance capability and maturity assessments and to increase their flexibility, a Granularity 'Filter' (Succar, 2009) with four Granularity Levels (GLevels) has been developed. Progression from low to higher levels of granularity indicates an increase in (i) assessment breadth, (ii) scoring detail, (iv) formality *and* (iv) assessor specialisation.

Using high-granularity levels (GLevels 3 or 4) exposes more detailed Competency Areas than low-granularity levels (GLevels 1 or 2). This variability in breadth, detail, formality and specialisation enables the preparation of several BIM performance measurement tools ranging from low-detail, informal and self-administered assessments to high-detail, formal and specialist-led appraisals. Table 8 below provides more information about the four Granularity Levels:

Table 8. BIM Competency Granularity Filter

COMPETENCY GRANULARITY FILTER

GLevel Number, GLevel Name, Description and Scoring System (Numerical and/or Named)			OScale applicability	Assessment By, Report Type and *Guide Name*	
1	**Discovery**	A low detail assessment used for basic and semi-formal discovery of BIM Capability and Maturity. Discovery assessments yield a basic numerical score.	All Scales	Self	Discovery Notes *BIMC&M Discovery Guide*
2	**Evaluation**	A more detailed assessment of BIM Capability and Maturity. Evaluation assessments yield a detailed numerical score.	All Scales	Self and Peer	Evaluation Sheets *BIMC&M Evaluation Guide*
3	**Certification**	A highly-detailed appraisal of those Competency Areas applicable across disciplines, markets and sectors. Certification appraisal is used for Structured (Staged) Capability and Maturity and yields a formal, Named Maturity Level.	8 and 9	External Consultant	Certificate *BIMC&M Certification Guide*
4	**Auditing**	The most comprehensive appraisal...In addition to competencies covered under Certification, Auditing appraises detailed Competency Areas including those specific to a market, discipline or a sector. Audits are highly customisable, suitable for Non-structured (Continuous) Capability and Maturity and yield a Named Maturity Level plus a Numerical Maturity Score for each Competency Area audited.	8, 9, 10 & 11	Self, Peer and External Consultant	Audit Report *BIMC&M Auditing Guide*

The mind map depicted in Section 2 identifies thirty-four Competency Areas available at GLevel 2 (Evaluation) as compared to only ten areas available at GLevel 1 (Discovery). Figure 10 below explores BIM Competencies at GLevel 3 (Certification) and GLevel 4 (Auditing):

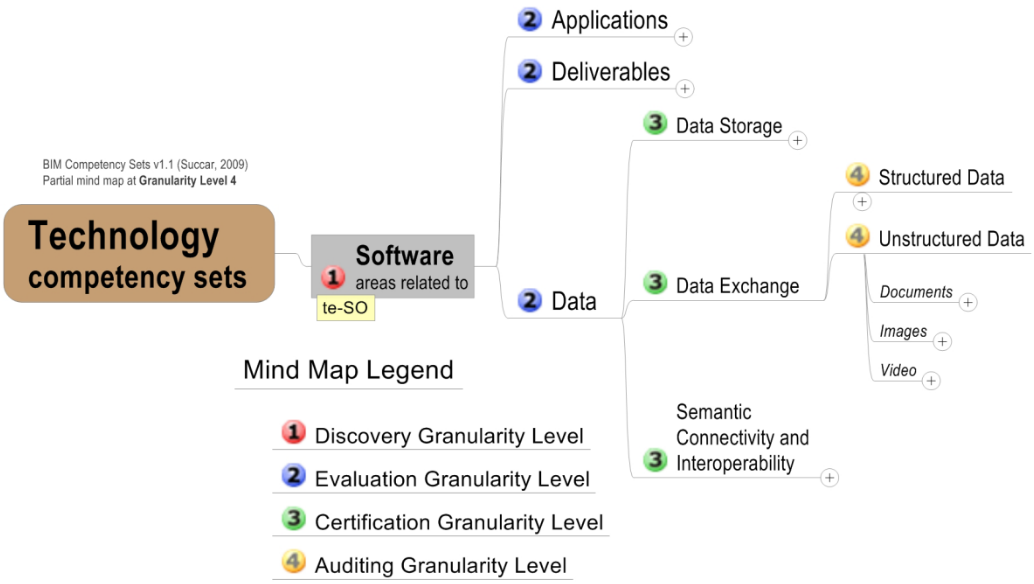


Figure 10. Competency Areas at Granularity Level 4 – partial mind map v1.1

As depicted above, the number and specificity of BIM Competencies increase dramatically at higher GLevels unveiling granular Areas like Data Storage, Data Exchange and Semantic Connectivity (at GLevel 3) and Structured and Unstructured Data (at GLevel 4). Additional more-specific competencies (not shown) include metadata, analytical models and other computable and non-computable formats (Kong et al., 2005) (Mathes, 2004) (Fallon & Palmer, 2007).

In addition to granularity, the number of Competency Areas applicable to teams and organisations varies according to Organisational Scale and Capability Stage. For example, the number of Competency Areas an 'Organisational Member' is evaluated against are less than that of a 'Project Team'. Similarly, the number of Competency Areas available for assessment within a Collaborative BIM project (BIM Stage 2) is less than that available within an Integrated one (BIM Stage 3). This variability is represented in Figure 11 below:

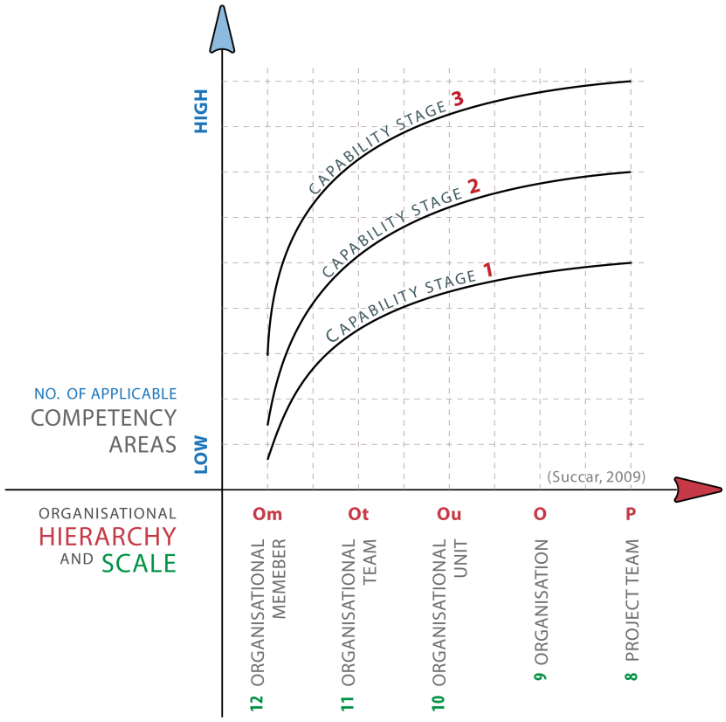


Figure 11. Applicability of Competency Areas relative to Organisational Scale and Capability Stage – diagram covering MICRO and MESO Organisational Scales v1.1

Assessment Workflow and Reporting

BIM Capability and Maturity assessments can be employed at either one of three Capability Stages (Table 2), one of twelve Organisational Scales (Table 3) and at one of four Competency Granularity Levels (Table 8). To manage all these assessment and reporting configurations, a simple assessment and reporting workflow has been developed (Figure 12):

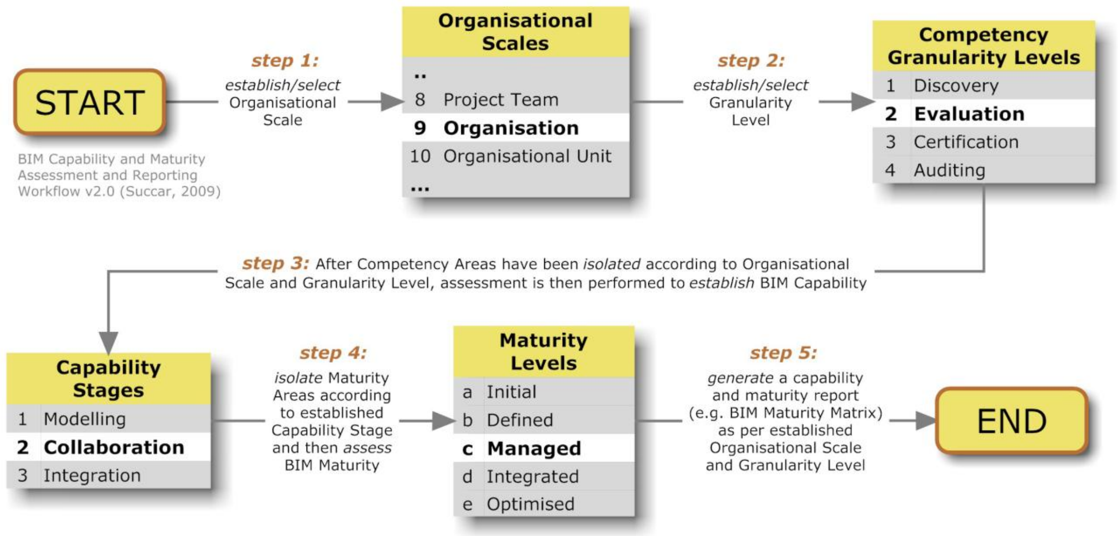


Figure 12. BIM Capability and Maturity Assessment and Reporting Workflow Diagram - v2.0

Expanding on the above diagram, a total of five workflow steps is needed to conduct a BIM Capability and Maturity Assessment. Starting with an extensive pool of generic BIM Competencies - applicable across AECO disciplines and organisational sizes – assessors first filter out non-applicable Competency Sets, conduct a series of assessments based on remaining Competency Areas and then generate a suitable Assessment Report:

Workflow Step 1: The assessor establishes the Organisational Scale (OScale) of the assessed. For example, an organisation with multiple offices across different cities may decide to assess BIM Capability and Maturity across the whole Organisation or within one specific Organisational Unit. To a varying degree (refer to Table 8), assessments can be conducted at every one of the twelve OScales. This ranges from 'Markets' (e.g. evaluating international standards and the availability of supplier-generated BIM components), through 'Project Teams' (e.g. assessing collaboration dynamics and risk-mitigation protocols within a team) to 'Organisational Members' (e.g. assessing BIM competencies of an individual architect or engineer). In this first workflow step, the selection/application of an OScale filter considerably reduces the number of applicable competencies.

Workflow Step 2: The assessor establishes assessment' Granularity Level (GLevel). There are up to four GLevels which can apply according to established OScale (refer to Table 8). Once a GLevel is set, non-applicable and more granular Competency Areas are removed from the assessment pool.

Workflow Step 3: After the number of applicable BIM Competencies has been significantly reduced by OScale and GLevel filters, the assessor establishes the 'actual' and the 'target' BIM Capability Stages. For example, if the assessed organisation – an architectural firm - has object-based modelling capability and aims to start collaborating with a structural engineer *then* BIM Stage 1 is the 'actual stage' while BIM Stage 2 is the 'target stage'. Armed with this knowledge, the assessor isolates Capability Sets A and B (refer to Figure 6) for focused capability assessment. The assessor then establishes wether each of the remaining applicable competencies has reached 'minimum capability'.

Workflow Step 4: The assessor isolates the BIM Competencies which reached 'minimum capability' and then assesses their maturity. Using the same example from workflow step 2, the assessor focuses his/her attention on Competency Sets A and B and then assess them individually against the five Maturity Levels.

Workflow Step 5: In the last workflow step, assessment results are reported using a template matching previously established OScale and GLevel. As per table 8, there are four types of assessment reports which vary in formality, coverage, detail and the provision of a named or numerical score.

Assessment Representation

Maturity assessments can be extensive in nature and may generate a significant amount of information that needs to be understood and acted upon. Knowledge visualisations can be employed to 'abstract' the BIM assessment deliverables and control their complexity by removing unnecessary detail (Kao & Archer, 1997). They are also instrumental in facilitating knowledge transfer to others (Eppler & Burkhard, 2005) as well as measuring BIM capability/ maturity against set visual benchmarks.

In addition to textual (e.g. the static BIM Maturity Matrix depicted in Section 4), assessments can be delivered in graphical (e.g. data-driven charts), multimedia (e.g. scenario-based online assessments) or through other types of knowledge visualisations (See example - Figure 13). These graphical representations allow visual comparisons between organisations or against an industry-wide average. They can also be used to help explain seemingly complex assessment results and promote action by teams and organisations.

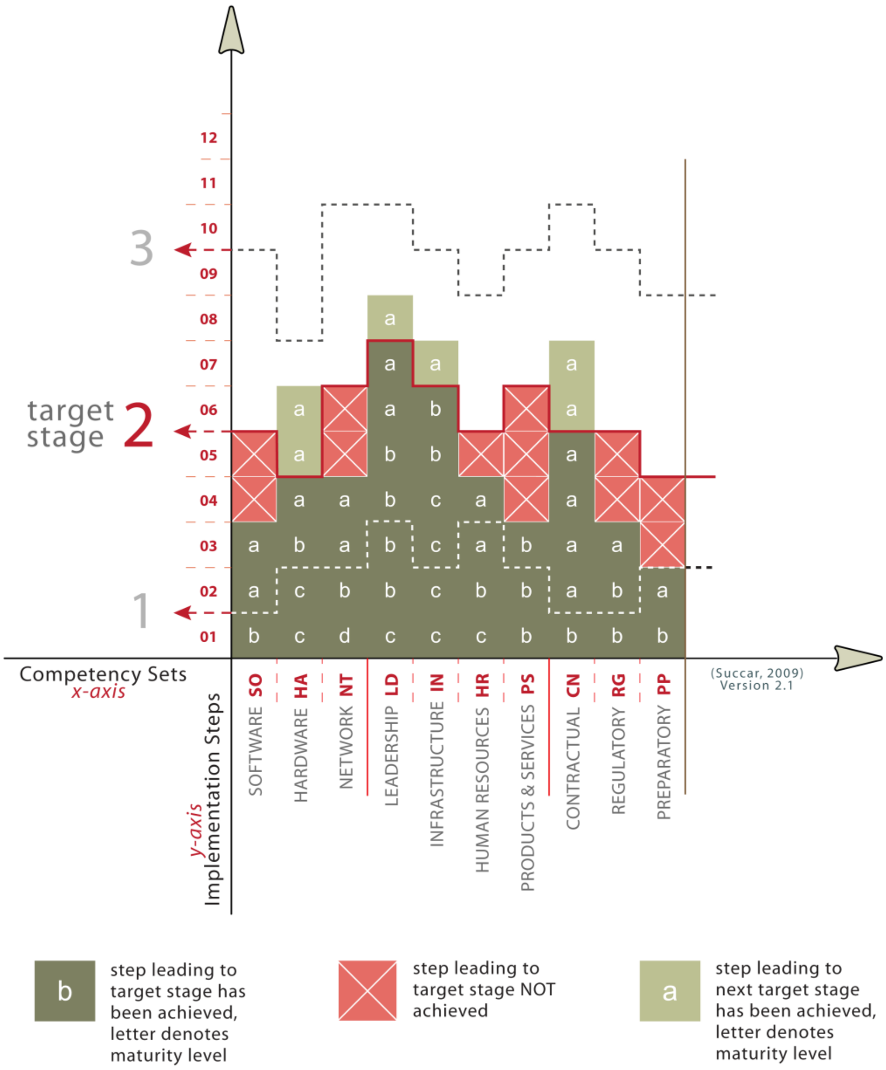


Figure 13. Visual Report of a hypothetical BIM Capability and Maturity assessment – v2.0

Sample Maturity Scoring System

Measuring BIM Capability and Maturity across markets, disciplines and organisational sizes requires an extensive, consistent yet flexible scoring system. Below is an exploration of the simplest form of scoring – called Maturity Discovery Score – to be used for informal, self-administered assessments at any Organisational Scale. The Discovery scoring system follows a simple arithmetic model:

- There are twelve individual scores relating to ten Competency Areas, one Capability Stage and one Organisational Scale.
- Maturity Levels are assigned a fixed number of maturity points: Level a (10 points), Level b (20 points), Level c (30 points), Level d (40 points) and Level e (50 points).
- The Maturity Discovery Score is the *average of* total points subdivided by twelve.

Table 9 below provides a hypothetical Maturity Discovery Score of an assessed organisation at BIM Capability Stage 2:

Table 9. Maturity Discovery Score - hypothetical maturity assessment at Granularity Level 1

MATURITY DISCOVERY SCORE

BIM Maturity Matrix Assessment at Granularity Level 1		a 10 Pts	b 20 Pts	c 30 Pts	d 40 Pts	e 50 Pts
Technology	Software			●		
	Hardware	●				
	Network		●			
Process	Leadership				●	
	Human Resources			●		
	Infrastructure		●			
	Products & Services		●			
Policy	Contractual		●			
	Regulatory			●		
	Preparatory				●	
Stage	Collaboration [2]			●		
Scale	Organisation [9]		●			
Subtotal		**10**	**100**	**120**	**80**	**0**
Total Points						**310**
Maturity Score						**25.83**
NOT SUITABLE FOR CERTIFICATION						

7 A Final Note

The BIM Maturity Matrix builds upon the BIM Framework (Succar, 2009) which identifies BIM Fields, Stages, Lenses, Steps, Project Lifecycle Phases and a specialised conceptual Ontology. This chapter further extends the Framework by developing a BIM Maturity Index, an Organisational Hierarchy/Scale and a Competency Granularity Filter. It also introduces the BIM Maturity Matrix, a Capability and Maturity assessment and reporting tool that utilizes all the above components.

The availability of an extended BIM Maturity Matrix (especially in a database-driven web format) will be beneficial to construction industry stakeholders irrespective of their Design, Construction or Operations' role. Industry practitioners can employ the Matrix and its underlying BIM Framework to:

- Increase their capability across a pre-identified range of technology, process and policy steps. As these competencies mature, they typically "meet an organisation's functional and quality expectations" (Jaco, 2004), get 'institutionalised' through standards, and organisational structures (McCormack and Johnson 2000) and help teams and organisations achieve *consistency in capability* (Vaidyanathan & Howell, 2007).
- Accurately assess their own, their peers' and potential project-partners' capability and maturity at selective organisational scales and granularity levels.
- Work towards a BIM 'performance excellence award', a BIM 'maturity certificate' or similar. Such awards are potentially beneficial for product/service differentiation as well as market positioning.
- Continuously assess and improve their BIM performance.

The BIM Maturity Matrix and its underlying BIM Framework are still being developed and extended. Future deliverables include a web-based interactive tool suitable for low-granularity, self-administered maturity assessment. Capability and maturity templates, questionnaires, guides, knowledge models and granular scoring systems are also being researched, developed and tested.

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KEY TERMS AND DEFINITIONS

BIM Fields

BIM Fields are conceptual clusters of domain players interacting and overlapping within the AECO industry. There are three BIM Field Types (Technology, Process and Policy) and three Field Components (Players, Requirements and Deliverables).

BIM Capability Stages

BIM Capability is the basic ability to perform a task, deliver a service or generate a product. BIM Capability Stages define the major milestones to be achieved by teams and organisations as they adopt BIM technologies and concepts. BIM Stages are defined by their *minimum requirements*.

BIM Lenses

BIM Lenses are distinctive layers of analysis which allow the researchers to selectively focus on any aspect of the AECO industry and generate knowledge views that either (a) highlight observables which meet the research criteria or (b) filter out those that do not.

BIM Steps

BIM Steps are the evolutionary or incremental steps that need to be completed to reach or progress within a BIM Stage (also see BIM Competency Sets below).

BIM Competency Sets

A BIM Competency Set is a hierarchical collection of individual competencies identified for the purposes of BIM implementation and assessment. If BIM Competencies are used for the purposes of active implementation, they are referred to as BIM Steps. However, if used for assessing existing implementations, they are referred to as BIM Areas.

BIM Organisational Scales

The BIM Organisational Scale is a hierarchical subdivision of markets, industries, project teams and organisations for the purpose of BIM capability and maturity measurement.

BIM Maturity Index

The term 'BIM maturity' refers to the *quality, repeatability and degrees of excellence* within a BIM capability. As opposed to 'capability' which denotes a *minimum ability*, maturity denotes the *extent of that ability*. The BIM Maturity Index (BIMMI) is a process improvement framework – with five distinct levels - developed to assess the maturity of BIM players, their requirements and deliverables across organisational scales.

BIM Maturity Matrix

The BIM Maturity Matrix (BIm^3) is a performance assessment and improvement tool which incorporates BIM Stages, Competency Sets, Organisational Scales and Granularity Levels.

PAPER A4

The Five Components of BIM Performance Measurement

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Download paper: http://bit.ly/BIMPaperA4

The Five Components of BIM Performance Measurement

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Abstract

Building Information Modelling (BIM) is an expansive knowledge domain within the Design, Construction and Operation (DCO) industry[1]. The voluminous possibilities attributed to BIM represent an array of challenges that can be met through a systematic research and delivery framework spawning a set of performance assessment and improvement metrics. This paper identifies five complementary components specifically developed to enable such assessment: [1] BIM Capability Stages representing transformational milestones along the implementation continuum [2] BIM Maturity Levels representing the quality, predictability and variability within BIM Stages, [3] BIM Competencies representing incremental progressions towards and improvements within BIM Stages, [4] Organisational Scales representing the diversity of markets, disciplines and company sizes and [5] Granularity Levels enabling highly-targeted yet flexible performance analyses ranging from informal self-assessment to high-detail, formal organisational audits. This paper explores these complementary components and positions them as a systematic method to understand BIM performance and to enable its assessment and improvement.

Keywords: Building Information Modelling, Performance Assessment and Improvement, Capability and Maturity Models

[1] There is no widely used term-definition which is equally representative of all planning-to-demolition activities within the construction industry. The author opted – after experimenting with many available acronyms like AEC, AECO, AECOO and AEC/FM - to adopt DCO as a preferred acronym as it builds upon the three major project lifecycle phases (Succar, 2009a).

1. Building Information Modelling: a brief introduction

Building Information Modelling (BIM) is a set of interacting policies, processes and technologies (Succar, 2009a) generating a "methodology to manage the essential building design and project data in digital format throughout the building's life-cycle" (Penttilä, 2006). This definition is one of tens of attempts to delimit the BIM domain which continues to expand in coverage and connotation. It is important – if we acknowledge BIM's value to the DCO industry and are inclined to favour its systemic adoption - to identify the domain's knowledge structures, internal dynamics and implementation requirements.

Some signs of the proliferation of BIM

There are many signs that the use of Building Information Modelling tools and processes is reaching a tipping point in some markets[2]. An increasing number of large institutional clients[3] - within the US for example - now stipulate object-based 3D models as the medium for accepting project submissions. Other signs include the abundance of BIM-specific software tools, books[4], blogs[5], tweets[6], tags[7] and reports from trusted market watchers[8].

Issues arising from the proliferation of BIM

The abundance of industry discussions and academic literature professing the ability of BIM methodologies to increase productivity has not yet been coupled with the availability of metrics and knowledge tools to reliably measure this productivity. Also, organisations attempting to *generate new* or *enhance existing* BIM deliverables can find little guidance towards identifying and prioritizing their respective requirements. This mismatch between *expected BIM deliverables* and *unforeseen BIM requirement*s increases the risks, costs and difficulties associated with BIM implementation, allows the proliferation of 'BIM wash' – falsely professing the ability to deliver BIM services or products - and prevents industry players from achieving their BIM potential.

[2] Refer to "Interoperability in the Construction Industry SmartMarket Report", a review of the research conducted by McGraw-Hill Construction Analytics during late-Spring 2007 (http://bit.ly/SMarket07) and McGraw-Hill's 2009 report "The Business Value of BIM: Getting Building Information Modeling to the Bottom Line" (http://bit.ly/SMarket09 - PDF 4MBs)

[3] Refer to relevant announcements by the US State of Wisconsin – Department of Administration (http://bit.ly/WisconsinBIM) and Texas Facilities Commission (http://bit.ly/TexasBIM) among others.

[4] Refer to basic search results like http://bit.ly/GoogleBooks_BIM or http://bit.ly/AmazonBooks_BIM

[5] Refer to blog search engine results similar to http://bit.ly/GoogleBlogs_BIM

[6] Refer to Tweet searches for the term BIM and/or IPD http://twitter.com/#search?q=bim%20ipd

[7] Refer to searches on Delicious http://bit.ly/Delicious_BIM and Digg http://digg.com/search?s=BIM

[8] Examples include the Building Design + Construction's Top 170 BIM Adopters ranking; part of the 2009 Giants 300 survey (http://bit.ly/Giants09).

2. The need for BIM performance metrics

The development of BIM performance metrics is a pre-requisite for BIM performance improvement. On one hand and without metrics, teams and organisations are unable to consistently measure their own successes or failures. Without measurement, no meaningful performance improvements may be achieved, financial investments may be misplaced and much efficiency may be lost. On the other hand and with the availability of measurement metrics, teams and organisations will be able to assess their own BIM competencies or compare them against an industry benchmark. Also, a valid set of BIM metrics will lay the foundations for a formal certification system which can be employed by industry leaders, governmental authorities and large facility owners/procurers to pre-select BIM service providers and attest to the quality of their deliverables.

2.1 Developing metrics and benchmarks

While it is important to develop metrics and benchmarks for BIM performance assessment, it is equally important for those metrics to be consistently accurate and adaptable to different industry sectors and organisational sizes. Much insight can be gained from performance measurement tools developed for other industries (Succar, 2009b); however, it is impractical to rely on any tool which is not specifically designed to measure key BIM deliverables/requirements or is not equally applicable across the construction supply chain.

This paper discusses a set of metrics purposefully developed to measure the specifics of BIM performance. To increase their reliability, adoptability and usability by different stakeholders, the metrics have been tailored to conform to a set of guiding principles partially discussed below:

Accurate: metrics are clear, falsifiable and allow accurate, repeatable assessment.

Applicable: metrics can be utilised by all stakeholders across Project Lifecycle Phases.

Attainable: benchmarks can be achieved through progressive accumulation of defined actions.

Consistent: when conducted by different assessors, measurements still yield the same results.

Cumulative: benchmarks are set as logical progressions; deliverables from one benchmark act as prerequisites for another.

Flexible: assessments can be performed across markets, organisational scales and their subdivisions.

Informative: measurements provide “feedback for improvement” and “guidance for next steps” (Nightingale and Mize, 2002).

Neutral: measurements do not prejudice proprietary, non-proprietary, closed, open, free or commercial solutions or schemata.

Specific: metrics are well defined and serve industry-specific assessment purposes.

Usable: metrics are intuitive and can be easily employed to assess BIM performance.

Based on the above guiding principles, the sections below introduce a set of complementary knowledge components which enable BIM performance assessment and facilitate its improvement:

3. Assessment components

There are five BIM Framework components (Succar, 2009a, Succar, 2009b) required to enable accurate and consistent BIM performance measurement:

3.1 BIM Capability Stages

BIM Capability is the basic ability to perform a task or deliver a BIM service/product. BIM Capability Stages (or BIM Stages) define the *minimum BIM requirements* - the major milestones that need to be reached by teams or organisations as they implement BIM technologies and concepts. Three BIM Stages separate 'pre-BIM', a fixed starting point representing *industry status before* BIM implementation, from 'post-BIM', a variable ending point representing the *ever evolving goal*[9] of employing *virtually integrated* Design, Construction and Operation (*vi*DCO) tools and concepts:

BIM Stage 1: object-based modelling

BIM Stage 2: model-based collaboration

BIM Stage 3: network-based integration

BIM Stages are defined by their *minimum* requirements. As an example, for an organisation to be considered at BIM Capability Stage 1, it needs to have deployed an object-based modelling software tool similar to ArchiCAD, Revit, Tekla or Constructor. Similarly for BIM Capability Stage 2, an organisation needs to be part of a multidisciplinary 'model-based' collaborative project. To be considered at BIM Capability Stage 3, an organisation needs to be using a network-based solution (like model servers or BIMSaaS[10]) to share object-based models with at least two other disciplines. Each of the three Capability Stages is further subdivided into Competency Steps. What differentiates stages from steps is that stages are *transformational* or *radical* changes while steps are *incremental* ones (Henderson and Clark, 1990) (Taylor and Levitt, 2005). The collection of steps required when working towards or within a BIM Stage - across the continuum from pre-BIM to post-BIM - is driven by different *perquisites for*, *challenges within* and *deliverables of* each BIM Stage. In addition to their type (the Competency Set they belong to – refer Section 3.3 below), BIM Steps can be also identified according to their location on the continuum (Fig. 1):

A Steps: from pre-BIM Status leading to BIM Stage 1

B Steps: from BIM Stage 1 leading towards BIM Stage 2

C Steps from BIM Stage 2 leading towards BIM Stage 3

D Steps from BIM Stage 3 leading towards post-BIM

[9] The author has stopped using the term Integrated Project Delivery (IPD) to represent the *ultimate goal of* implementing BIM (AIA, 2007) to prevent any confusion with the term's evolving contractual connotations.
[10] Building Information Modelling Software As A Service, refer to http://bit.ly/BIMbits & http://bit.ly/BIMaaS

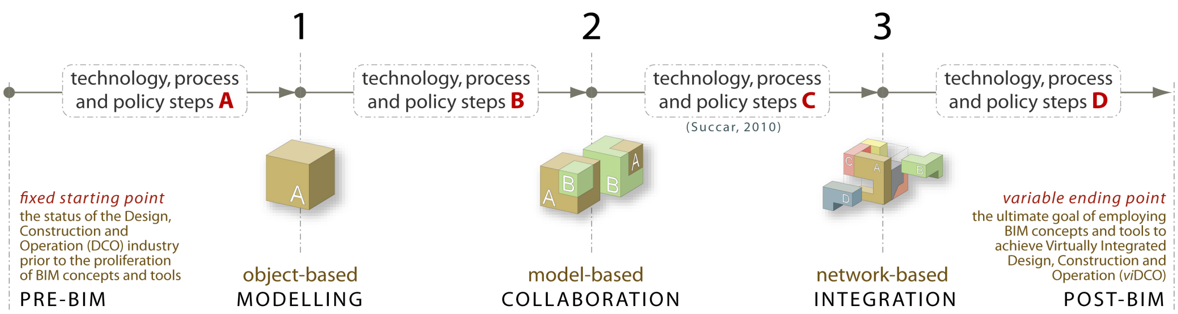

Fig. 1. Step Sets leading to or separating BIM Stages – v1.1

3.2 BIM Maturity Levels

The term 'BIM Maturity' refers to the quality, repeatability and degree of excellence within a BIM Capability. That is, as opposed to 'capability' which denotes a *minimum ability* (refer to Section 3.1), 'maturity' denotes *the extent of that ability* in performing a task or delivering a BIM service/product. BIM Maturity's benchmarks are performance improvement milestones (or levels) that teams and organisations aspire to or work towards. In general, the progression from low to higher levels of maturity indicate (i) better control through minimising variations between performance targets and actual results, (ii) better predictability and forecasting by lowering variability in competency, performance and costs, and (iii) greater effectiveness in reaching defined goals and setting new more ambitious ones (Lockamy III and McCormack, 2004) (McCormack, Ladeira and Oliveira, 2008).

The concept of BIM Maturity has been adopted from SEI's Capability Maturity Model (SEI, 2008), a process improvement framework initially intended as a tool to evaluate the ability of government contractors to deliver a software project. CMM originated in the field of quality management (Crosby, 1979) and was later developed in 1980s for the benefit of the US Department of Defence (Hutchinson and Finnemore, 1999). It's successor, the more comprehensive Capability Maturity Model Integration (CMMI), continues to be developed and extended by the Software Engineering Institute, Carnegie Mellon University. There are also other varieties of CMMs across many industries (Succar, 2009b) but they are all - in essence – specialised frameworks to assist stakeholders in improving their capability (Jaco, 2004) and achieving process improvement benefits. These include increased productivity and Return On Investment (ROI) as well as reduced costs and post-delivery defects (Hutchinson and Finnemore, 1999).

Maturity models are typically composed of multiple maturity *levels* - process improvement 'building blocks' or 'components' (Paulk, Weber, Garcia, Chrissis and Bush, 1993). When the requirements of each level are satisfied, implementers can then build on top of established components to attempt 'higher' maturity. Although CMMs are not without their detractors (Weinberg, 1993) (Jones, 1994) (Bach, 1994), research conducted within other industries have already identified the correlation between improving process maturity and business performance (Lockamy III and McCormack, 2004).

The ‘original’ software industry CMM, however, is not applicable to the construction industry as it does not address supply chain issues, and its maturity levels do not account for the different phases of a project lifecycle (Sarshar, Haigh, Finnemore, Aouad, Barrett, Baldry and Sexton, 2000). Although there are other efforts – derived from CMM - which focus on the construction industry (Succar, 2009b), there is no comprehensive maturity model/index that can be applied to BIM, its implementation stages, players, deliverables or its effect on project lifecycle phases.

To address this shortfall, the BIM Maturity Index (BIMMI) has been developed by analysing and then integrating several maturity models used across different industries (Succar, 2009b). It has been customised to reflect the specifics of BIM capability, implementation requirements, performance targets and quality management. The BIM Maturity Index has five distinct levels: (**a**) **Initial/ Ad-hoc**, (**b**) **Defined**, (**c**) **Managed**, (**d**) **Integrated** and (**e**) **Optimised** (Fig. 2). Level names have been chosen through comparing terminology used by many maturity models followed by selecting those easily understandable by DCO stakeholders and able to reflect increasing BIM maturity from ad-hoc to continuous improvement (Succar, 2009b).

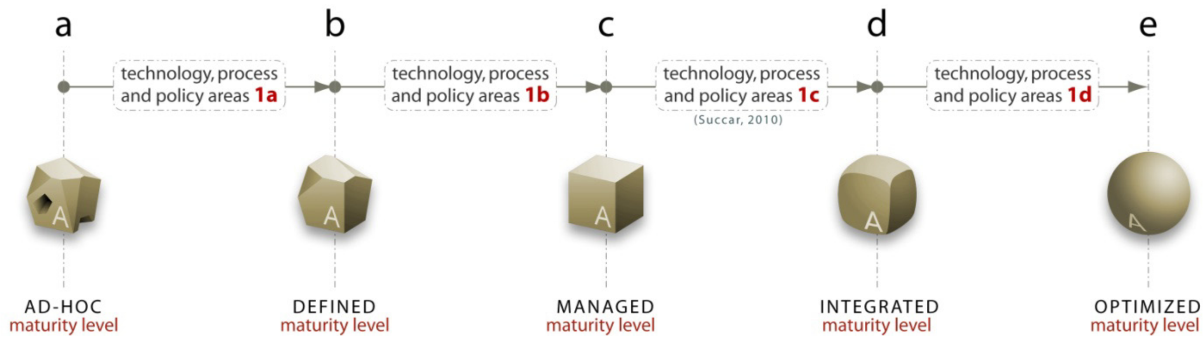

Fig. 2. Building Information Modelling Maturity Levels at BIM Stage 1

3.3 BIM Competency Sets

A BIM Competency Set is a hierarchical collection of individual competencies identified for the purposes of BIM implementation and assessment. The term Competency – as used by the author - does not necessarily reflect human abilities but a generic set of abilities suitable for implementing as well as assessing BIM Capability and/or Maturity. If a BIM Competency Set is used for active implementation, they are referred to as BIM Implementation Steps. However, if used for assessing existing implementations, they are referred to as BIM Assessment Areas. The below diagram (Fig. 3) reflects how the BIM Framework (Succar, 2009a) generates BIM Competency Sets out of multiple Fields[11], Stages and Lenses[12]:

[11] BIM Fields are conceptual clusters of domain players interacting and overlapping within the DCO industry (Succar, 2009a). There are three BIM Field Types (Technology, Process and Policy) and three Field Components (Players, Requirements and Deliverables).

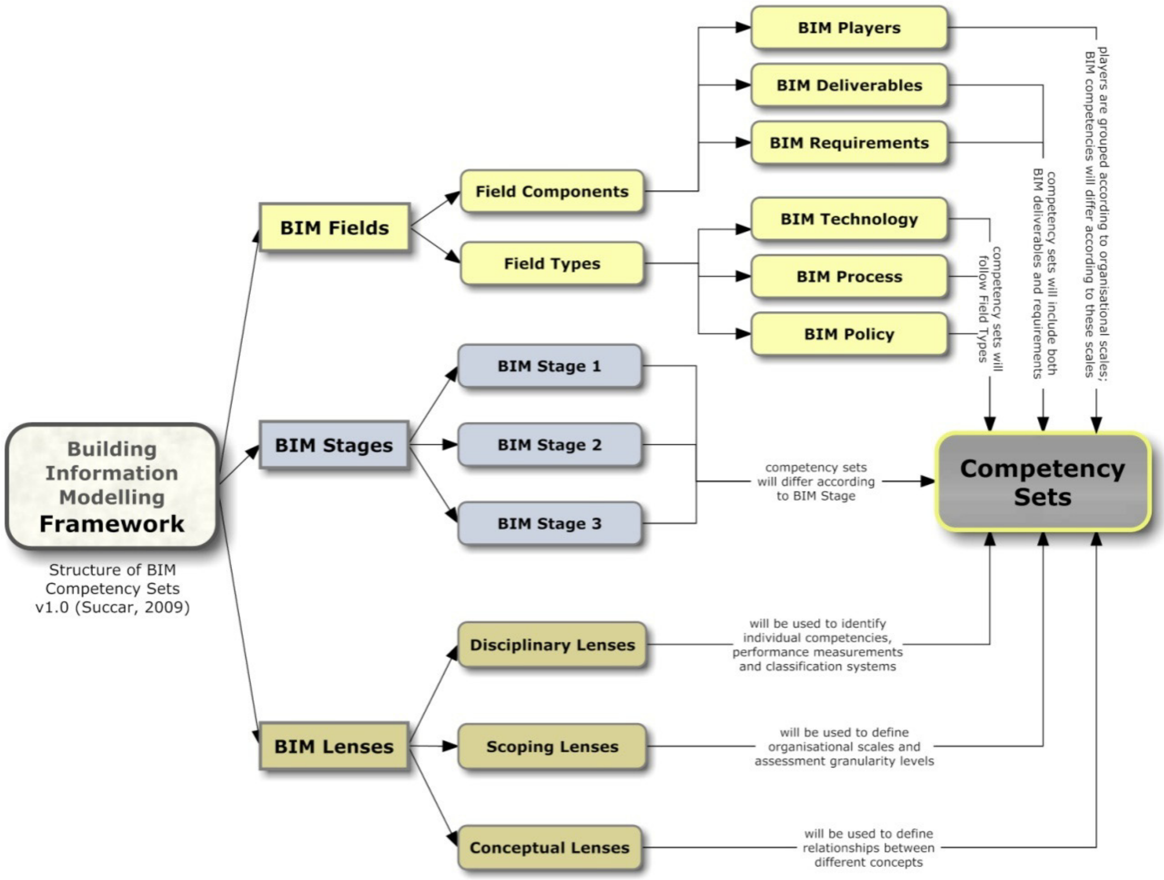

Fig. 3. Structure of BIM Competency Sets v1.0

BIM Competencies are a direct reflection of BIM Requirements and Deliverables and can be grouped into three sets – Technology, Process and Policy:

Technology sets in *software, hardware* and *networks*. For example, the availability of a BIM tool allows the migration from drafting-based to object-based workflow (a requirement of BIM Stage 1)

Process sets in *leadership, infrastructure, human Resources* and *products/services*. For example, collaboration processes and database-sharing skills are necessary to allow model-based collaboration (BIM Stage 2).

Policy sets in *contracts, regulations* and *research/education*. For example, alliance-based or risk-sharing contractual agreements are pre-requisites to network-based integration (BIM Stage 3).

Below (Fig. 4) is a partial mind map of BIM Competency Sets shown at Granularity Level 2 (to understand Granularity Levels, please refer to Section 3.5):

[12] BIM Lenses are distinctive layers of analysis which allow domain researchers to selectively focus on any aspect of the DCO industry and generate knowledge views that either (a) highlight observables which meet the research criteria or (b) filter out those which do not (Succar, 2009a).

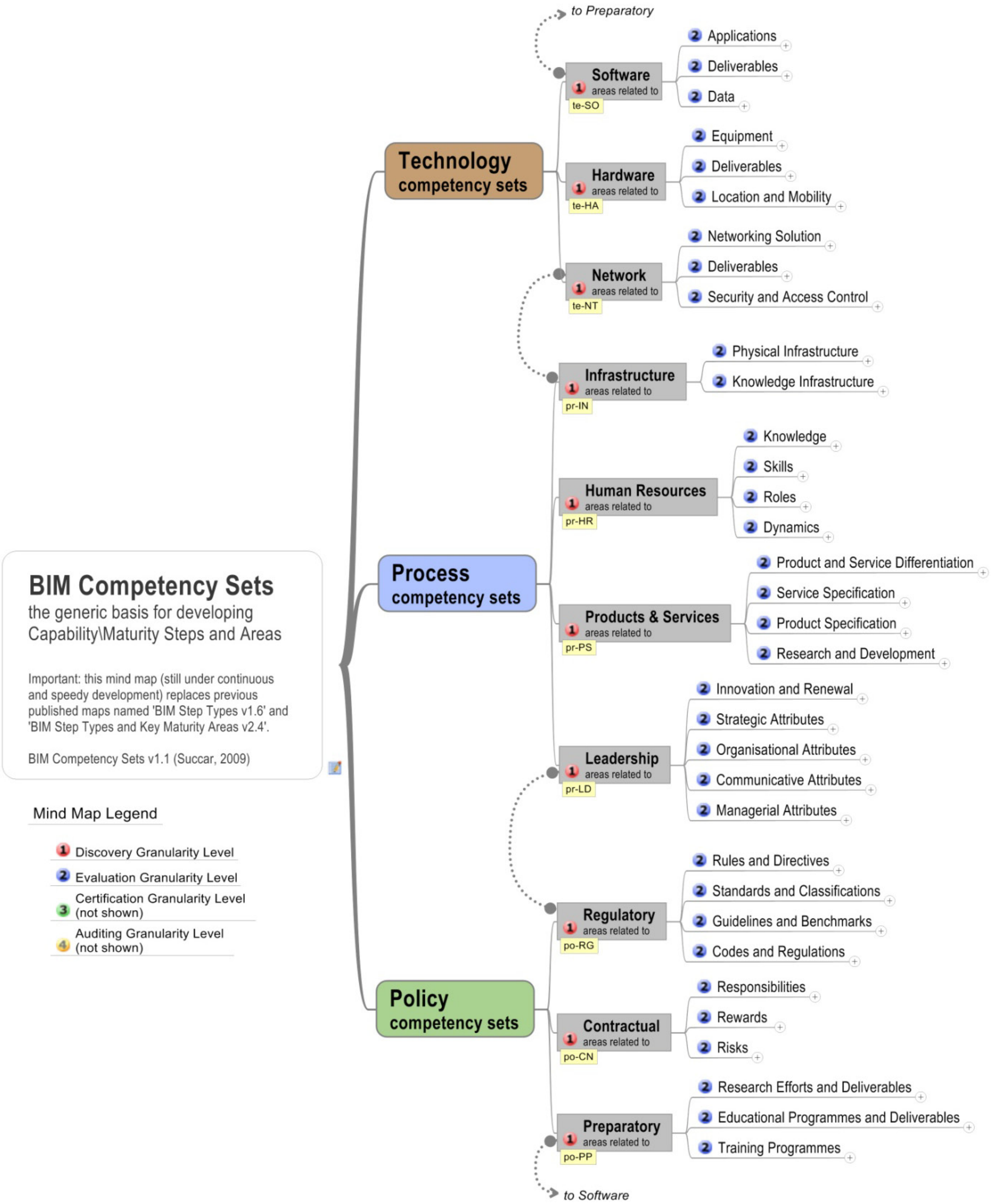

Fig. 4. BIM Competency Sets v1.1 – shown at Granularity Level 2

3.4 BIM Organisational Scales

To allow BIM performance assessments to respect the diversity of markets, disciplines and company sizes, an Organisational Scale (OScale) has been developed. The Scale can be used to customise assessment efforts and is depicted in Table 1 below:

Table 1. Organisational Scale

Low Detail			**High Detail**			
Name	**Sym**	**Granularity**	**Name**	**Sym**	**Granularity**	**Short Definition**
MACRO Markets and Industries	**M**	Markets 1	(Macro M)	**M**	Market 1	Markets are the “world of commercial activity where goods and services are bought and sold” http://bit.ly/pjB3c
			(Meso M)	**Md**	Defined Market 2	Defined Markets can be geographical, geopolitical or resultant from multi-party agreements similar to NAFTA or ASIAN.
			(Micro M)	**Ms**	Sub-Market 3	Sub-markets can be local or regional.
	I	Industries 4	(Macro I)	**I**	Industry 4	Industries are 'the organised action of making of goods and services for sale'. Industries can traverse markets and may be service, product or project-based. The AEC industry is mostly Project-Based. http://bit.ly/ielY3
			(Meso I)	**Is**	Sector 5	A sector is a "distinct subset of a market, society, industry, or economy whose components share similar characteristics" http://bit.ly/15UkZD
			(Micro I)	**Id**	Discipline 6	Disciplines are industry sectors, “branches of knowledge, systems of rules of conduct or methods of practice”. http://bit.ly/7jT82
				Isp	Specialty 7	Specialty is a focus area of knowledge, expertise, production or service within a sub-discipline.
MESO Projects and their teams	**P**	Project Teams 8	n/a	**P**	Project Team 8	Project Teams are temporary groupings of organisations with the aim of fulfilling predefined objectives of a project - a planned endeavour, usually with a specific goal and accomplished in several steps or stages. http://bit.ly/dqMYg
MICRO Organisations Units, their Teams & Members	**O**	Organisations 9	(Macro O)	**O**	Organisation 9	An organisation is a 'social arrangement which pursues collective goals, which controls its own performance, and which has a boundary separating it from its environment. http://bit.ly/v7p9N
			(Meso O)	**Ou**	Organisational Unit 10	Departments and Units are specialised divisions of an organisation. These can be co-located or distributed geographically.
				Ot	Organisational Team 11	Organisational Teams consist of a group of individuals (human resources) assigned to perform an activity or deliver a set of assigned objectives. Teams can be physically co-located or formed across geographical or departmental lines.
			(Micro O)	**Om**	Organisational Member 12	Organisational members can be part of multiple Organisational Teams.

3.5 BIM Granularity Levels

Competency Sets include a large number of individual competencies grouped under numerous competency headings (refer to Fig. 4). To enhance BIM Capability and Maturity assessments and to increase their flexibility, a Granularity 'filter' with four Granularity Levels (GLevels) has been developed. Progression from lower to higher levels of granularity indicates an increase in (i) assessment breadth, (ii) scoring detail, (iv) formality and (iv) assessor specialisation.

Using higher-granularity levels (GLevels 3 or 4) exposes more detailed Competency Areas than lower-granularity levels (GLevels 1 or 2). This variability in breadth, detail, formality and specialisation enables the preparation of several BIM performance measurement tools ranging from low-detail, informal and self-administered assessments to high-detail, formal and specialist-led appraisals. Table 2 below provides more information about the four Granularity Levels:

Table 2. BIM Competency Granularity Levels v2.1

GLevel Number, GLevel Name, Description and Scoring System (Numerical and/or Named)			OScale applicability	Assessment By, Report Type and *Guide Name*	
1	**Discovery**	A low detail assessment used for basic and semi-formal discovery of BIM Capability and Maturity. Discovery assessments yield a basic numerical score.	All Scales	Self	Discovery Notes *BIMC&M Discovery Guide*
2	**Evaluation**	A more detailed assessment of BIM Capability and Maturity. Evaluation assessments yield a detailed numerical score.	All Scales	Self and Peer	Evaluation Sheets *BIMC&M Evaluation Guide*
3	**Certification**	A highly-detailed appraisal of those Competency Areas applicable across disciplines, markets and sectors. Certification appraisal is used for Structured (Staged) Capability and Maturity and yields a formal, Named Maturity Level.	8 and 9	External Consultant	Certificate *BIMC&M Certification Guide*
4	**Auditing**	The most comprehensive appraisal...In addition to competencies covered under Certification, Auditing appraises detailed Competency Areas including those specific to a market, discipline or a sector. Audits are highly customisable, suitable for Non-structured (Continuous) Capability and Maturity and yield a Named Maturity Level plus a Numerical Maturity Score for each Competency Area audited.	8, 9, 10 & 11	Self, Peer and External Consultant	Audit Report *BIMC&M Auditing Guide*

Granularity Levels thus increase or decrease the number of Competency Areas used for performance assessment. For example, the mind map provided in Fig. 4 reveals **ten Competency Areas** at GLevel 1 and **thirty-four Competency Areas** at GLevel 2. Also, at GLevels 3 and 4, the number of Competency Areas available for performance assessment increase dramatically as depicted in Fig. 5:

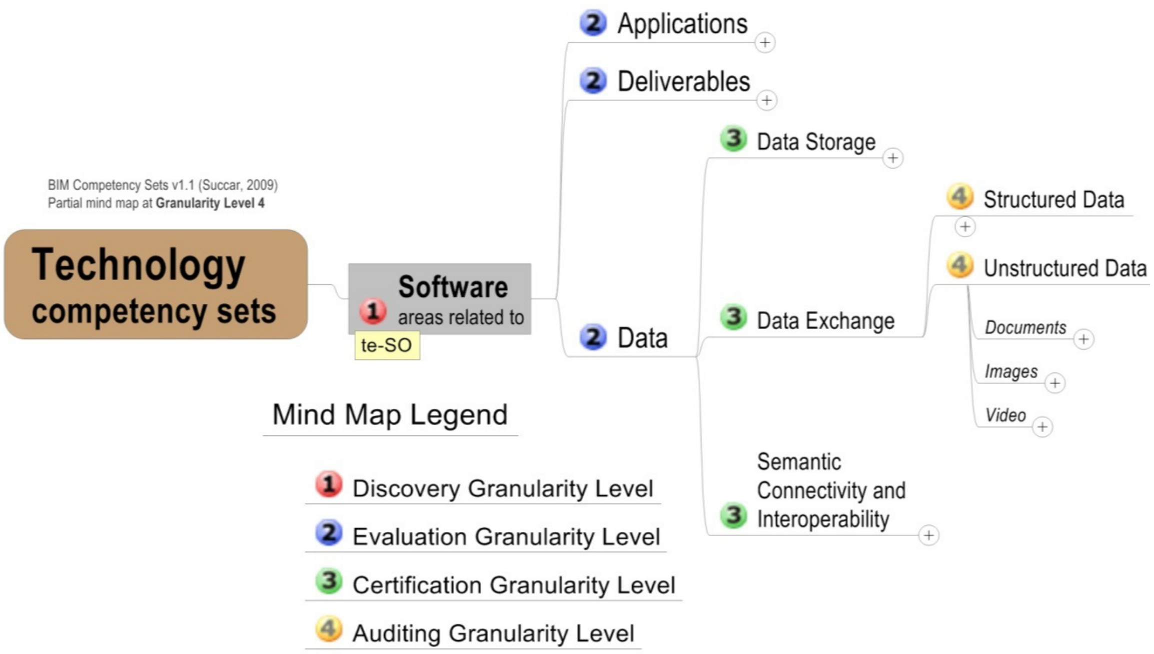

Fig. 5. Technology Competency Areas at Granularity Level 4 – partial mind map v1.1

The partial mind map depicted in Fig. 5 unveils many additional Competency Areas under GLevel 3 like Data Storage and Date Exchange. At GLevel 4, the map unveils even more-detailed Competency Areas like Structured and Unstructured Data which in-turn branch into computable and non-computable components (Kong, Li, Liang, Hung, Anumba and Chen, 2005) (Mathes, 2004) (Fallon and Palmer, 2007).

4. Applying the five assessment components

Using the above five complementary Framework components, BIM performance assessments can be conducted - in conformance with the guiding principles discussed in Section 2.1 - at multiple combinations of Capability, Maturity, Competency, Organisational Scale and Granularity. To manage all possible configurations, a simple assessment and reporting workflow has been developed (Fig. 6):

Fig. 6. BIM Capability and Maturity Assessment and Reporting Workflow Diagram - v2.0

Expanding on the above diagram, a total of five workflow steps are needed to conduct a BIM performance assessment. Starting with an extensive pool of generic BIM Competencies - applicable across DCO disciplines and organisational sizes – assessors can first filter-out non-applicable Competency Sets, conduct a series of assessments based on remaining Competencies and then generate a suitable Assessment Report.

5. In Summary

The five BIM Framework components, briefly discussed in this paper, enable an array of assessment possibilities for DCO stakeholders to measure and improve their BIM performance. These components complement each other and enable highly-targeted yet flexible performance analyses ranging from informal self-assessment to high-detail and formal organisational audits. Such a system of assessment can be utilised to standardize BIM implementation and assessment efforts, enable a structured approach to BIM education and training as well as establish a solid base for a formal BIM certification process. The five components and other related assessment, scoring and reporting tools are currently being extended, tested and validated. A mechanism for identifying and continuously updating BIM Competencies by subject matter experts is actively being developed. Also, a sample online tool (focusing on a sample discipline, at a sample granularity) is currently being formulated. Once conceptual validation, field testing and tool calibration are successfully conducted, the five components may be well-placed to consistently assess, and by extension improve, BIM performance.

Acknowledgement

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PAPER A5

Measuring BIM performance: Five metrics

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ARTICLE

Measuring BIM performance: Five metrics

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Abstract
The term Building Information Modelling (BIM) refers to an expansive knowledge domain within the design, construction and operation (DCO) industry. The voluminous possibilities attributed to BIM represent an array of challenges that can be met through a systematic research and delivery framework spawning a set of performance assessment and improvement metrics. This article identifies five complementary components specifically developed to enable such assessment: (i) BIM capability stages representing transformational milestones along the implementation continuum; (ii) BIM maturity levels representing the quality, predictability and variability within BIM stages; (iii) BIM competencies representing incremental progressions towards and improvements within BIM stages; (iv) Organizational Scales representing the diversity of markets, disciplines and company sizes; and (v) Granularity Levels enabling highly targeted yet flexible performance analyses ranging from informal self-assessment to high-detail, formal organizational audits. This article explores these complementary components and positions them as a systematic method to understand BIM performance and to enable its assessment and improvement. A flowchart of the contents of this article is provided.

■ *Keywords* – Building Information Modelling; capability and maturity models; performance assessment and improvement

A BRIEF INTRODUCTION TO BUILDING INFORMATION MODELLING (BIM)

BIM is a term that is used by different authors in many different ways (Figure 1). The nuances between their definitions highlight the rapid growth the area has experienced, as well as the potential for confusion to arise when ill-defined terminology is used to communicate specific meanings. In the context of this article, BIM refers to a set of interacting *policies*, *processes* and *technologies* (illustrated in Figure 2) that generate a 'methodology to manage the essential building design and project data in digital format throughout the building's life-cycle' (Penttilä, 2006). It is important to identify the knowledge structures, internal dynamics and implementation requirements of BIM if confusion and duplication of effort are to be avoided.

SOME INDICATORS OF THE PROLIFERATION OF BIM

There are many signs that the use of BIM tools and processes is reaching a tipping point in some markets (Keller, Gerjets, Scheiter, & Garsoffky, 2006; McGraw-Hill, 2009). For example, in the USA an increasing number of large institutional clients now require object-based three-dimensional (3D) models to be provided as a part of tender submissions (Ollerenshaw, Aidman, & Kidd, 1997). Furthermore, the UK Cabinet Office has recently published a construction strategy article that requires the submission of a 'fully collaborative 3D BIM (with all project and asset information, documentation and data being electronic) as a minimum by 2016' (BIS, 2011; UKCO, 2011, p. 14). Other signs include the abundance of BIM-specific software tools, books, new media tools and reports (Eppler & Platts, 2009).

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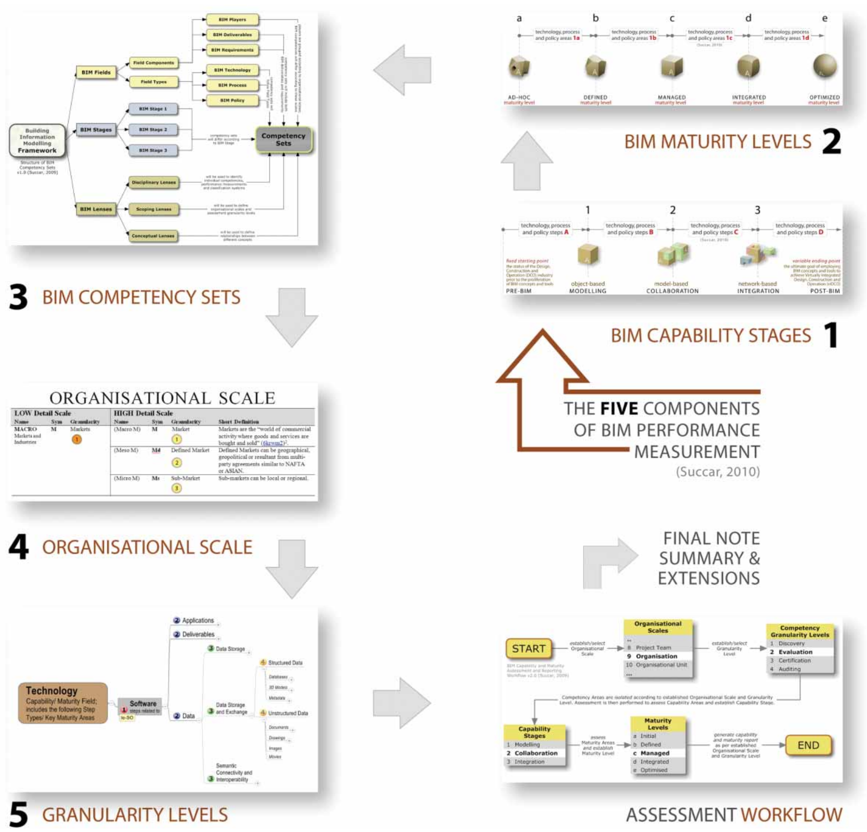


FIGURE 1 Flowchart of the contents of this article

ISSUES ARISING FROM THE PROLIFERATION OF BIM

Notwithstanding the much-touted benefits of BIM as a means of increasing productivity, there are currently few metrics that measure such improvements. Furthermore, little guidance is available for organizations wishing to *generate new* or *enhance* their *existing* BIM deliverables. Those wishing to adopt BIM or identify and/or prioritize their requirements are thus left to their own devices. The implementation of any new technology is fraught with challenges and BIM is no exception. In addition, those implementing BIM frequently expect to be able to realize significant benefits and productivity gains while they are still inexperienced users. Successful implementation of these systems requires an appreciation of how BIM resources (including hardware, software as well as the technical and management skills of staff) need to evolve in harmony with each other. The multiple and varied understandings that practitioners have of BIM further compound the difficulties they experience. When the unforeseen happens, the risks, costs and difficulties associated with implementing BIM increase. In such circumstances compromises are likely to be made leading, in turn, to users' expectations not being met.

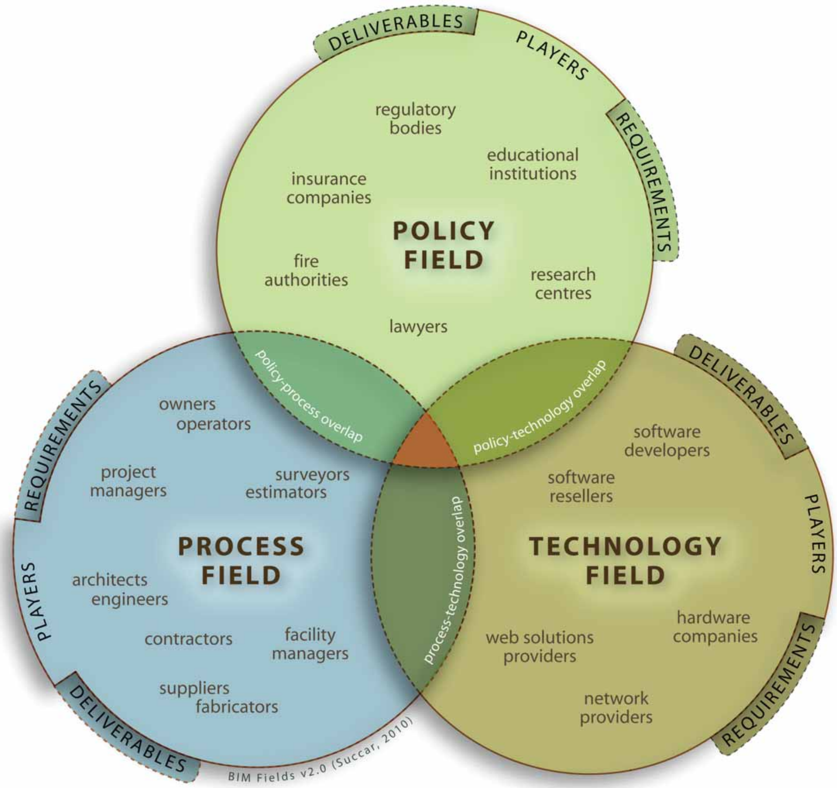


FIGURE 2 The interlocking fields of BIM activity

THE NEED FOR BIM PERFORMANCE METRICS

BIM use needs to be assessable if the productivity improvements that result from its implementation are to be made apparent. Without such metrics, teams and organizations are unable to consistently measure their own successes and/or failures. Performance metrics enable teams and organizations to assess their own competencies in using BIM and, potentially, to benchmark their progress against that of other practitioners. Furthermore, robust sets of BIM metrics lay the foundations for formal certification systems, which could be used by those procuring construction projects to pre-select BIM service providers.

DEVELOPING BIM METRICS AND BENCHMARKS

Although it is important to develop metrics and benchmarks for BIM performance assessment, it is equally important that these metrics are accurate and able to be adapted to different industry sectors and organizations. Considerable insight can be gained from the performance measurement tools developed for other industries but it would be foolhardy to rely on any tool which is not designed for the specific requirements of the task in question. Those required to measure key BIM deliverables/requirements across the construction supply chain are no exception.

This article describes a set of metrics purposefully developed to measure the specifics of BIM performance. To increase their reliability, adoptability and usability for different stakeholders, the first-named author identified the following performance criteria. The metrics should be:

- *Accurate*: Well-defined and able to measure performance at high levels of precision.
- *Applicable*: Able to be utilized by all stakeholders across all phases of a project's lifecycle.
- *Attainable*: Achievable if defined actions are undertaken.
- *Consistent*: Yield the same results when conducted by different assessors.
- *Cumulative*: Set as logical progressions; deliverables from one act as prerequisites for another.
- *Flexible*: Able to be performed across markets, Organizational Scales and their subdivisions.
- *Informative*: Provide 'feedback for improvement' and 'guidance for next steps' (Nightingale & Mize, 2002, p. 19).
- *Neutral*: Not prejudice proprietary, non-proprietary, closed, open, free or commercial solutions or schemata.
- *Specific*: Serve the specific requirements of the *construction industry.*
- *Universal*: Apply equally across markets and geographies.
- *Usable*: Intuitive and able to be easily employed to assess BIM performance.

This article describes the development of a set of BIM performance metrics based on these guiding principles. It introduces a set of complementary knowledge components that enable BIM performance assessment and facilitate its improvement.

RESEARCH DESIGN

The investigations described in this article are part of a larger PhD study which addresses the question of how to represent BIM knowledge structures and provide models that facilitate the implementation of BIM in academic and industrial settings. It is grounded in a set of paradigms, theories, concepts and experiences which combine to form the view of the BIM domain reported here.

CONCEPTUAL BACKGROUND

According to Maxwell (2005), the conceptual background underpinning a study such as this is typically based on several sources including previous research and existing theories, the researcher's own experiential knowledge and thought experiments. Various theories (including systems theory (Ackoff, 1971; Chun, Sohn, Arling, & Granados, 2008), systems thinking (Chun et al., 2008), diffusion of innovation theory (Fox & Hietanen, 2007; Mutai, 2009; Rogers, 1995), technology acceptance models (Davis, 1989; Venkatesh & Davis, 2000) and complexity theory (Froese, 2010; Homer-Dixon, 2001) assisted in analysing the BIM domain and enriched the study's conceptual background. Constraints identified in these theories led to the development of a new theoretical framework based on an inductive approach '[more suitable for researchers who are more concerned about] the correspondence of their findings to the real world than their coherence with existing theories or laws' (Meredith, Raturi, Amoako-Gyampah, & Kaplan, 1989, p. 307).

METHODOLOGY AND VALIDATION

The five components of BIM performance measurement are some of the deliverables of the BIM framework developed after assessing numerous publicly available international guidelines (Succar, 2009). The framework itself is composed of a number of high-level concepts that interact to generate a set of guides and tools necessary to (i) facilitate BIM implementations; (ii) conduct BIM performance assessments; and (iii) generate multi-tiered educational curricula.

The theoretical underpinnings of the BIM framework have been generated through a process of inductive inference (Michalski, 1987), conceptual clustering (Michalski & Stepp, 1987) and reflective learning (Van der Heijden & Eden, 1998; Walker, Bourne, & Shelley, 2008). Framework components were then represented visually through a series of 'knowledge models' to reduce topic complexity (Tergan, 2003) and facilitate knowledge transfer to others (Eppler & Burkhard, 2005).

Many of the BIM framework's components – fields, stages, lenses, steps, competencies and several visual knowledge models – have been subjected to a process of validation through a series of international focus groups employing a mixed-model approach (Tashakkori & Teddlie, 1998). The results from these focus groups and their impact on the development of the five components of BIM performance measurement will be published separately.

THE FIVE COMPONENTS OF BIM PERFORMANCE MEASUREMENT

The first named author identified five BIM framework components as those required to enable accurate and consistent BIM performance measurement (Succar, 2010b). These include BIM capability stages, BIM maturity levels, BIM competency sets, Organizational Scales and Granularity Levels.

The following sections provide brief introductions to each component. They are followed by a step-by-step workflow which allows BIM capability and maturity assessments to be conducted.

BIM CAPABILITY STAGES

BIM capability is defined here as the basic ability to perform a task or deliver a BIM service/product. BIM capability stages (or BIM stages) define the *minimum BIM requirements* – the major milestones that need to be reached by teams or organizations as they implement BIM technologies and concepts. Three BIM stages separate 'pre-BIM', a fixed starting point representing *industry status before* BIM implementation, from 'post-BIM', a variable end-point representing the continually evolving goal of employing *virtually integrated* design, construction and operation (*vi*DCO) tools and concepts. (The term *vi*DCO is used in preference to integrated project delivery (IPD) as representing the ultimate goal of implementing BIM (AIA, 2007) to prevent any confusion with the term's evolving contractual connotations within the United States.) The stages are:

- *BIM stage 1*: object-based modelling;
- *BIM stage 2*: model-based collaboration;
- *BIM stage 3*: network-based integration.

BIM stages are defined by their *minimum* requirements. For example, to be considered as having achieved BIM capability stage 1, an organization needs to have deployed an object-based modelling software tool similar to ArchiCAD, Revit, Tekla or Vico. Similarly, for BIM capability stage 2, an organization needs to be engaged in a multidisciplinary 'model-based' collaborative project. To be considered at BIM capability stage 3, an organization needs to be using a network-based solution which links to external databases and shares object-based models with at least two other disciplines – a solution similar to a model server or BIMSaaS solution (BIMserver, 2011; Onuma, 2011; Wilkinson, 2008).

Each of these three capability stages may be further subdivided into competency steps. What differentiates stages from steps is that stages are *transformational* or *radical* changes, while steps are *incremental* ones (Henderson & Clark, 1990; Taylor & Levitt, 2005). The collection of steps involved in working towards or within a BIM stage (i.e. across the continuum from pre-BIM to post-BIM) is driven by different *perquisites for*, *challenges within* and *deliverables of* each BIM stage. In addition to their type (the competency set they belong to – refer to Section BIM competency sets), the following BIM steps can be also identified according to their location on the continuum shown in Figure 3:

- *A steps*: from pre-BIM status leading to BIM stage 1;
- *B steps*: from BIM stage 1 leading towards BIM stage 2;
- *C steps* from BIM stage 2 leading towards BIM stage 3;
- *D steps* from BIM stage 3 leading towards post-BIM.

BIM MATURITY LEVELS

The term 'BIM maturity' refers to the quality, repeatability and degree of excellence within a BIM capability. Although 'capability' denotes a *minimum ability* (refer to Section BIM capability stages), 'maturity' denotes *the extent of that ability* in performing a task or delivering a BIM service/product. BIM maturity's benchmarks are performance improvement milestones (or levels) that teams and organizations aspire to or

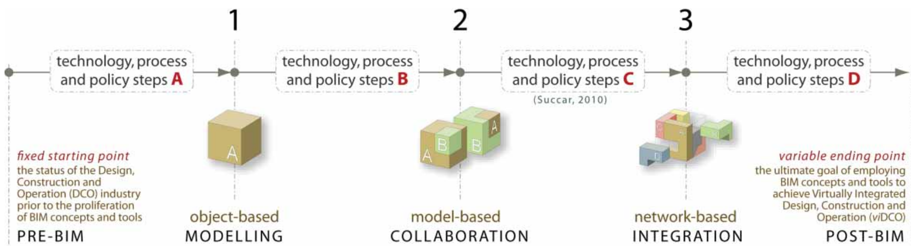


FIGURE 3 Step sets leading to or separating BIM stages – v1.1

work towards. In general, the progression from lower to higher levels of maturity indicates (i) improved control resulting from fewer variations between performance targets and actual results; (ii) enhanced predictability and forecasting of reaching cost, time and performance objectives; and (iii) greater effectiveness in reaching defined goals and setting new more ambitious ones (Lockamy III & McCormack, 2004) (McCormack, Ladeira, & Oliveira, 2008).

The concept of BIM maturity has been adopted from Software Engineering Institute's (SEI) capability maturity model (CMM) (SEI, 2008a), a process improvement framework initially intended as a tool to evaluate the ability of government contractors to deliver software projects. CMM originated in the field of quality management (Crosby, 1979) and was later developed for the benefit of the US Department of Defence (Hutchinson & Finnemore, 1999). Its successor, the more comprehensive capability maturity model integration (CMMI) (SEI, 2006a, 2006b, 2008c), continues to be developed and extended by the SEI, Carnegie Mellon University. Several CMM variants exist for other industries (Succar, 2010a) but they are all, in essence, specialized frameworks that assist stakeholders to improve their capabilities (Jaco, 2004) and benefit from process improvements. Example benefits include increased productivity and return on investment as well as reduced costs and post-delivery defects (Hutchinson & Finnemore, 1999).

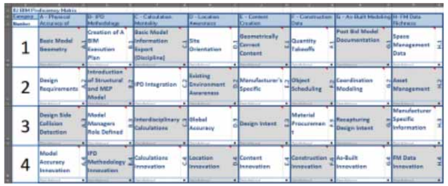
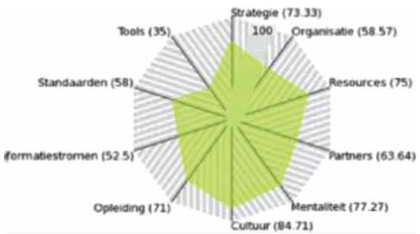
Maturity models are typically composed of multiple maturity *levels*, or process improvement 'building blocks' or 'components' (Paulk, Weber, Garcia, Chrissis, & Bush, 1993). When the requirements of each level are satisfied, implementers can then build on established components to attempt 'higher' maturity. Although CMMs are not without their detractors (e.g. Bach, 1994; Jones, 1994; Weinberg, 1993), research conducted in other industries has already identified a correlation between improved process maturity and business performance (Lockamy III & McCormack, 2004).

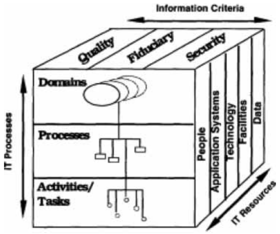
The 'original' software industry CMM, however, is not applicable to the construction industry. It does not address supply chain issues, and its maturity levels do not account for the different phases of the lifecycle of a construction project (Sarshar et al., 2000). Although other efforts, derived from CMM, focus on the construction industry (refer to Table 1), there is no comprehensive maturity model/index that can be applied to BIM, its implementation stages, players, deliverables or its effect on project lifecycle phases.

The CMMs listed in Table 1 are similar in structure and objectives but differ in conceptual depth, industrial focus, terminology and target audience. A common theme is how CMMs employ simple experience-based classifications and benchmarks to facilitate continuous improvement within organizations. In analysing their suitability for developing a BIM-specific maturity index, most are broad in approach and can collectively form a basis for a range of BIM processes, technologies and policies. However, none easily accommodates the size of organizations being monitored. Also, from a terminology standpoint, there is insufficient differentiation between the notion of capability (an ability to perform a task) and that of maturity (the degrees of excellence in performing a task). This differentiation is critical when catering for staged BIM implementation as it responds to the disruptive and expansive nature of BIM.

To address the aforementioned shortcomings, the BIM maturity index (BIMMI) has been developed by

TABLE 1 Maturity models influencing the BIM maturity index

SAMPLE REPRESENTATION	ABBREVIATION, NAME – *ORGANIZATION* DESCRIPTION AND NUMBER OF MATURITY LEVELS
 'Simplified matrix' – an Excel Worksheet from the BIM proficiency matrix (IU, 2009b)	BIM proficiency matrix – *The Indiana University Architect's Office* The BIM proficiency matrix is 'used to assess the proficiency of a respondent's skill at working in a BIM environment'. The matrix is 'adaptable to project needs' and intends to communicate 'owner intent regarding BIM objectives' (IU, 2009a, pp. 15 and 16) The BIM proficiency matrix is a static, multi-worksheet, MS Excel workbook (IU, 2009b) which includes eight categories to be assessed. Upon assessment, a score ranging from one to four points is assigned against each category. Points for each category are then tallied and the total BIM maturity score is calculated. The matrix identifies five 'BIM standards' which a project can achieve, should achieve or has already achieved depending on when the matrix is deployed The five proficiency levels (or BIM standards) are: 'working towards BIM' – the lowest standard, 'certified BIM', 'silver', 'gold' and 'ideal' – the highest BIM maturity standard
 Score representation (by category) from the sample BIM QuickScan report (TNO, 2010)	BIM QuickScan – *TNO Built Environment and Geosciences* The BIM QuickScan tool aims to 'serve as a standard BIM benchmarking instrument in the Netherlands'. The scan is intended to be performed 'in a limited time of maximum one day' (Sebastian & Van Berlo, 2010, pp. 255 and 258) The BIM QuickScan Tool is organized around four chapters: organization and management, mentality and culture, information structure and information flow, and tools and applications. 'Each chapter contains a number of KPIs in the form of a multiple-choice questionnaire. . . With each KPI, there are a number of possible answers. For each answer, a score is assigned. Each KPI also carries a certain weighting factor. The sum of all the partial scores after considering the weighting factors represents the total score of BIM performance of an organization' (Sebastian & Van Berlo, 2010, pp. 258 and 259) KPIs are assessed against a percentile score while 'Chapters', representing a collation of KPIs, are assessed against a five-level system (0 to 4).



(Lainhart, 2000)

COBIT, Control objects for information and related technology – *Information Systems Audit and Control Association (ISACA) and the IT Governance Institute (ITGI)*

The main objective of COBIT is to 'enable the development of clear policy and good practice for IT control throughout organizations' (Lainhart, 2000, p. 22)

The COBIT Maturity Model is 'an IT governance tool used to measure how well developed the management processes are with respect to internal controls. The maturity model allows an organization to grade itself from non-existent (0) to optimized (5)' (Pederiva, 2003, p. 1). COBIT includes six *maturity levels* (non-existent, initial/ad hoc, repeatable but intuitive, defined process, managed and measurable and optimized), four *domains* and 34 *control objectives*

Note: There is some alignment between ITIL (OGC, 2009) and COBIT with respect to IT governance within organizations (Sahibudin, Sharifi, & Ayat, 2008) of value to BIM implementation efforts

Level	Focus	Process Areas	Result
5 Optimizing	*Continuous process improvement*	Organizational Innovation & Deployment Causal Analysis and Resolution	Productivity & Quality
4 Quantitatively Managed	*Quantitative management*	Organizational Process Performance Quantitative Project Management	
3 Defined	*Process standardization*	Requirements Development Technical Solution Product Integration Verification Validation Organizational Process Focus Organizational Process Definition Organizational Training Integrated Project Management Risk Management Decision Analysis and Resolution	
2 Managed	*Basic project management*	Requirements Management Project Planning Project Monitoring & Control Supplier Agreement Management Measurement and Analysis Process & Product Quality Assurance Configuration Management	
1 Initial	*Competent people and heroics*		

Source: NASA, Software Engineering Process Group. http://bit.ly/CMMI-NASA

CMMI, Capability maturity model integration – *Software Engineering Institute/Carnegie Melon*

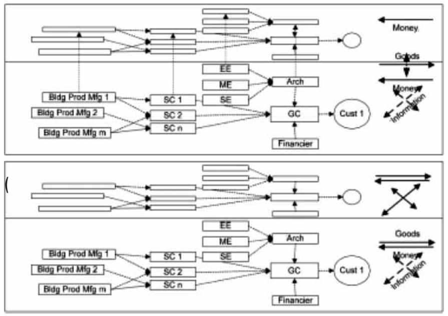
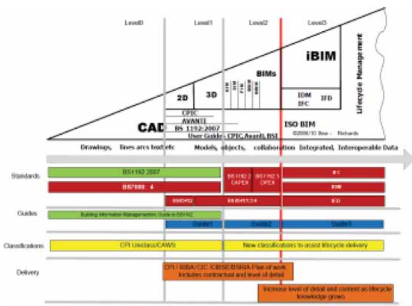
Capability maturity model® integration (CMMI) is a process improvement approach that helps integrate traditionally separate organizational functions, set process improvement goals and priorities, provide guidance for quality processes, and provide a point of reference for appraising current processes (SEI, 2006b, 2006c, 2008a, 2008b, 2008c)

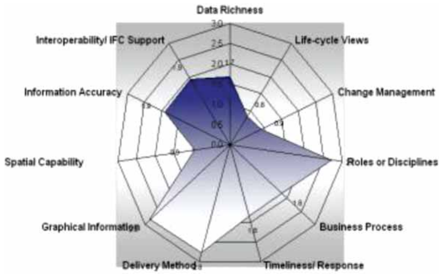
CMMI has five *maturity levels* (for staged representation, six capability levels for continuous representation), 16 core *process areas* (22 for CMMI-DEV and 24 for CMMI-SVC) and one to four *goals* for each process area

The five maturity levels are: initial, managed, defined, quantitatively managed and optimizing

Continued

TABLE 1 Continued

SAMPLE REPRESENTATION	ABBREVIATION, NAME – *ORGANIZATION* DESCRIPTION AND NUMBER OF MATURITY LEVELS
 (Vaidyanathan & Howell, 2007)	CSCMM, construction supply chain maturity model 'Construction supply chain management (CSCM) refers to the management of information, flow, and money in the development of a construction project' as mentioned in (Vaidyanathan & Howell, 2007, p. 170) CSCMM has four maturity stages: ad hoc, defined, managed and controlled
 (BIS, 2011)	iBIM – integrated Building Information Modelling The iBIM maturity model – introduced in Bew, Underwood, Wix, and Storer (2008) – has been devised 'to ensure clear articulation of the standards and guidance notes, their relationship to each other and how they can be applied to projects and contracts in industry' (BIS, 2011, p. 40) The iBIM model identifies specific capability targets (not performance milestones) for the UK Construction Industry covering technology, standards, guides, classifications and delivery (total number of topics not defined). Targets for each topic are organized under one or more loosely defined maturity levels (0–3)

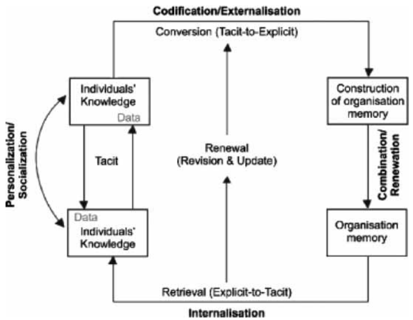


(Suermann, Issa, & McCuen, 2008)

I-CMM, Interactive capability maturity model – *National Institute for Building Sciences (NIBS) Facility Information Council (FIC)*

This I-CMM is closely coupled with the NBIMS effort (version1, part 1) and establishes 'a tool to determine the level of maturity of an individual BIM as measured against a set of weighted criteria agreed to be desirable in a Building Information Model' (Suermann, et al., 2008, p. 2; NIST, 2007; NIBS, 2007)

The ICMM has 11 'areas of interest' measured against 10 maturity levels



(Arif, Egbu, Alom, & Khalfan, 2009)

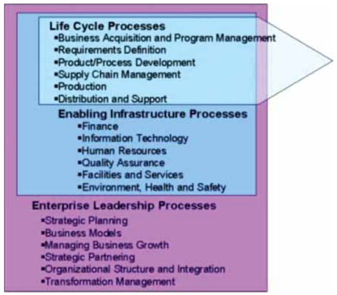
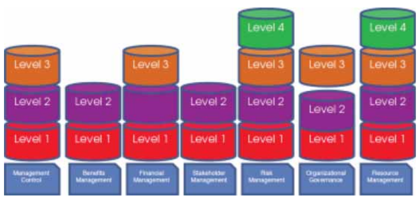
Knowledge retention maturity levels

Arif et al. (2009) introduced four levels of knowledge retention maturity

Knowledge management is an integral part of BIM capability and subsequent maturity. The matrix thus incorporates these levels: (i) knowledge is shared between employees, (ii) shared knowledge is documented (transferred from tacit to explicit), (iii) documented knowledge is stored and (iv) stored knowledge is accessible and easily retrievable (Arif, et al., 2009)

Continued

TABLE 1 Continued

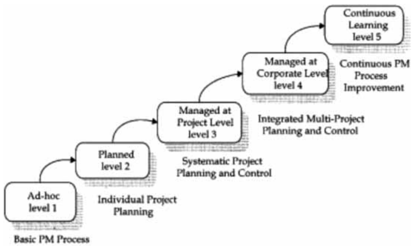
SAMPLE REPRESENTATION	ABBREVIATION, NAME – *ORGANIZATION* DESCRIPTION AND NUMBER OF MATURITY LEVELS
 (Nightingale & Mize, 2002)	LESAT, Lean Enterprise Self-Assessment Tool – *Lean Aerospace Initiative (LAI) at the Massachusetts Institute of Technology (MIT)* LESAT is focused on 'assessing the degree of maturity of an enterprise in its use of 'lean' principles and practices to achieve the best value for the enterprise and its stakeholders' (Nightingale & Mize, 2002, p. 17). LESAT has 54 lean practices organized within three assessment sections: lean transformation/leadership, life cycle processes and enabling infrastructure *and* five maturity levels: some awareness/sporadic, general awareness/informal, systemic approach, ongoing refinement and exceptional/innovative
 (OGC, 2008)	P3M3, Portfolio, programme and project management maturity model – *Office of Government Commerce* The P3M3 provides 'a framework with which organizations can assess their current performance and put in place improvement plans with measurable outcomes based on industry best practice' (OGC, 2008, p. 8) The P3M3 has five maturity levels: awareness, repeatable, defined, managed and optimized

(SEI, 2008d)

P-CMM®, People capability maturity model v2 – *Software Engineering Institute/Carnegie Melon*

P-CMM is an 'organizational change model' and a 'roadmap for implementing workforce practices that continuously improve the capability of an organization's workforce' (SEI, 2008d, pp. 3 and 15)

P-CMM has five maturity levels: initial, managed, defined, predictable and optimizing



(Kwak & Ibbs, 2002)

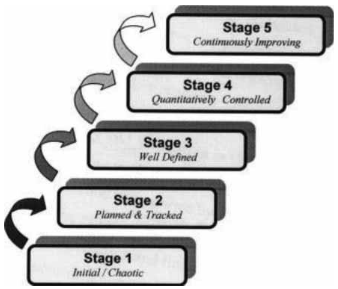
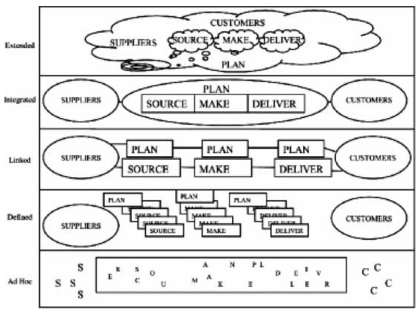
$(PM)^2$, Project management process maturity model

The project management process maturity $(PM)^2$ model 'determines and positions an organization's relative project management level with other organizations'. It also aims to integrate PM 'practices, processes, and maturity models to improve PM effectiveness in the organization' (Kwak & Ibbs, 2002, p. 150)

$(PM)^2$ has five maturity levels: initial, planned, managed at project level, managed at corporate level and continuous learning

Continued

TABLE 1 Continued

SAMPLE REPRESENTATION	ABBREVIATION, NAME – *ORGANIZATION* DESCRIPTION AND NUMBER OF MATURITY LEVELS
 (Hutchinson & Finnemore, 1999)	SPICE, Standardized process improvement for construction enterprises – *Research Centre for the Built and Human Environment, The University of Salford* SPICE is a project which developed a framework for continuous process improvement for the construction industry. SPICE is an 'evolutionary step-wise model utilizing experience from other sectors, such as manufacturing and IT' (Hutchinson & Finnemore, 1999, p. 576; Sarshar et al., 2000) SPICE has five stages: initial/chaotic, planned & tracked, well defined, quantitatively controlled, and continuously improving
 (Lockamy III & McCormack, 2004)	Supply chain management process maturity model *and* business process orientation (BPO) Maturity Model The model conceptualizes the relation between process maturity and supply chain operations as based on the supply-chain operations reference model (Stephens, 2001). The model's maturity describes the 'progression of activities toward effective SCM and process maturity. Each level contains characteristics associated with process maturity such as predictability, capability, control, effectiveness and efficiency' (Lockamy III & McCormack, 2004, p. 275; McCormack, 2001). The five maturity levels are: ad hoc, defined, linked, integrated and extended

Other maturity models – or variation on listed maturity models – include those on software process improvement (Hardgrave & Armstrong, 2005), IS/ICT management capability (Jaco, 2004), interoperability (Widergren, Levinson, Mater, & Drummond, 2010), project management (Crawford, 2006), competency (Gillies & Howard, 2003) and financial management (Doss, Chen, & Holland, 2008)

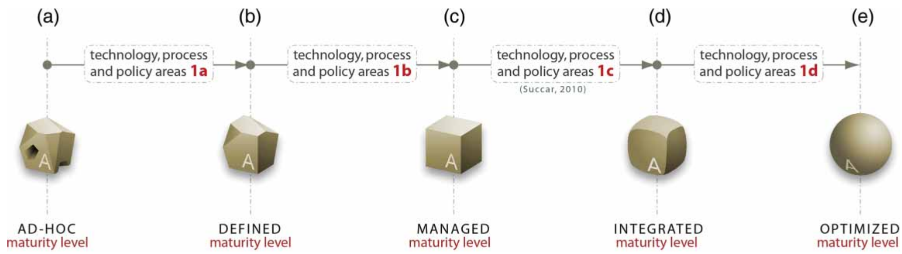


FIGURE 4 Building Information Modelling maturity levels at BIM stage 1

analysing and then integrating these and other maturity models used across different industries. The BIMMI has been customized to reflect the specifics of BIM capability, implementation requirements, performance targets and quality management. It has five distinct levels: (a) initial/ad hoc, (b) defined, (c) managed, (d) integrated and (e) optimized (Figure 4). Level names were chosen to reflect the terminology used in many maturity models, to be easily understandable by DCO stakeholders and to reflect increasing BIM maturity from ad hoc to continuous improvement (Table 2).

BIM COMPETENCY SETS

A BIM competency set is a hierarchical collection of individual competencies identified for the purposes of implementing and assessing BIM. In this context, the term competency reflects a generic set of abilities suitable for implementing as well as assessing BIM capability and/or maturity. Figure 5 illustrates how the BIM framework generates BIM competency sets out of multiple fields, stages and lenses (Succar, 2009).

BIM competencies are a direct reflection of BIM requirements and deliverables and can be grouped into three sets, namely technology, process and policy:

Technology sets in *software, hardware* and *data/networks*. For example, the availability of a BIM tool allows the migration from drafting-based to object-based workflow (a requirement of BIM stage 1)

Process sets in *resources, activities/workflows, products/services, and leadership/management*. For example, collaboration processes and database-sharing skills are necessary to allow model-based collaboration (BIM stage 2).

Policy sets in *benchmarks/controls, contracts/agreements and guidance/supervision*. For example, alliance-based or risk-sharing contractual agreements are pre-requisites for network-based integration (BIM stage 3).

Figure 6 provides a partial mind-map of BIM competency sets shown at Granularity Level 2 (for an explanation of Granularity Levels, please refer to Section BIM granularity levels).

BIM ORGANIZATIONAL SCALES

To allow BIM performance assessments to respect the diversity of markets, disciplines and company sizes, an Organizational Scale (OScale) has been developed. The scale can be used to customize assessment efforts and is depicted in Table 3.

BIM GRANULARITY LEVELS

Competency sets include a large number of individual competencies grouped under numerous headings (shown in Figure 6). To enhance BIM capability and maturity assessments and to increase their flexibility, a granularity 'filter' with four Granularity Levels (GLevels) has been developed. Progression from lower to higher levels of granularity indicates an increase in (i) assessment breadth, (ii) scoring detail, (iv) formality and (iv) assessor specialization.

Using higher Granularity Levels (GLevel 3 or 4) exposes more detailed competency areas than lower Granularity Levels (GLevel 1 or 2). This variability enables the preparation of several BIM performance measurement tools ranging from low-detail, informal and self-administered assessments to high-detail, formal and specialist-led appraisals. Table 4 provides more information about the four Granularity Levels.

TABLE 2 A non-exhaustive list of terminology used by CMMs to denote maturity levels including those used by the BIM maturity index

MATURITY MODELS	MATURITY LEVELS					
	0	1 *or* a	2 *or* b	3 *or* c	4 *or* d	5 *or* e
BIM maturity index		Initial/ad hoc	Defined	Managed	Integrated	Optimized
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

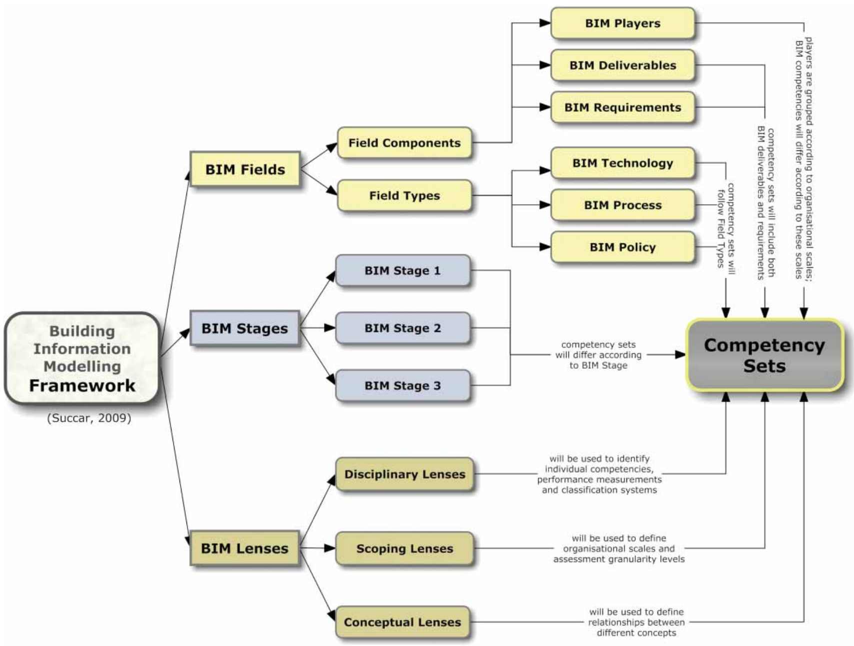


FIGURE 5 Structure of BIM competency sets v1.0

Granularity Levels increase or decrease the number of competency areas used for performance assessment. For example, the mind map provided in Figure 6 reveals *10 competency areas* at GLevel 1 and *41 competency areas* at GLevel 2. Also, at GLevels 3 and 4, the number of competency areas available for performance assessment increases dramatically as shown in Figure 7.

The partial mind-map shown in Figure 7 reveals many additional competency areas under GLevel 3, such as data types and data structures. At GLevel 4, the map reveals even more detailed competency areas including structured and unstructured data, which in turn branch into computable and non-computable components (Fallon & Palmer, 2007; Kong et al., 2005; Mathes, 2004).

APPLYING THE FIVE ASSESSMENT COMPONENTS

The aforementioned five complementary BIM framework components (capability stages, maturity levels, competency sets, Organizational Scales and Granularity Levels) allow performance assessments to be conducted involving combinations of these components. The guiding principles discussed in Section Developing BIM metrics and benchmarks all apply. To manage all possible configurations, a simple assessment and reporting workflow has been developed (Figure 8).

The workflow shown in Figure 8 identifies the five steps needed to conduct a BIM performance assessment. Starting with an extensive pool of generic BIM competencies – applicable across DCO disciplines and organizational sizes – assessors can first filter-out non-applicable competency sets, conduct a series of assessments based on the competencies remaining and then generate appropriate assessment reports.

A FINAL NOTE

The five BIM framework components, briefly discussed in this article, provide a range of

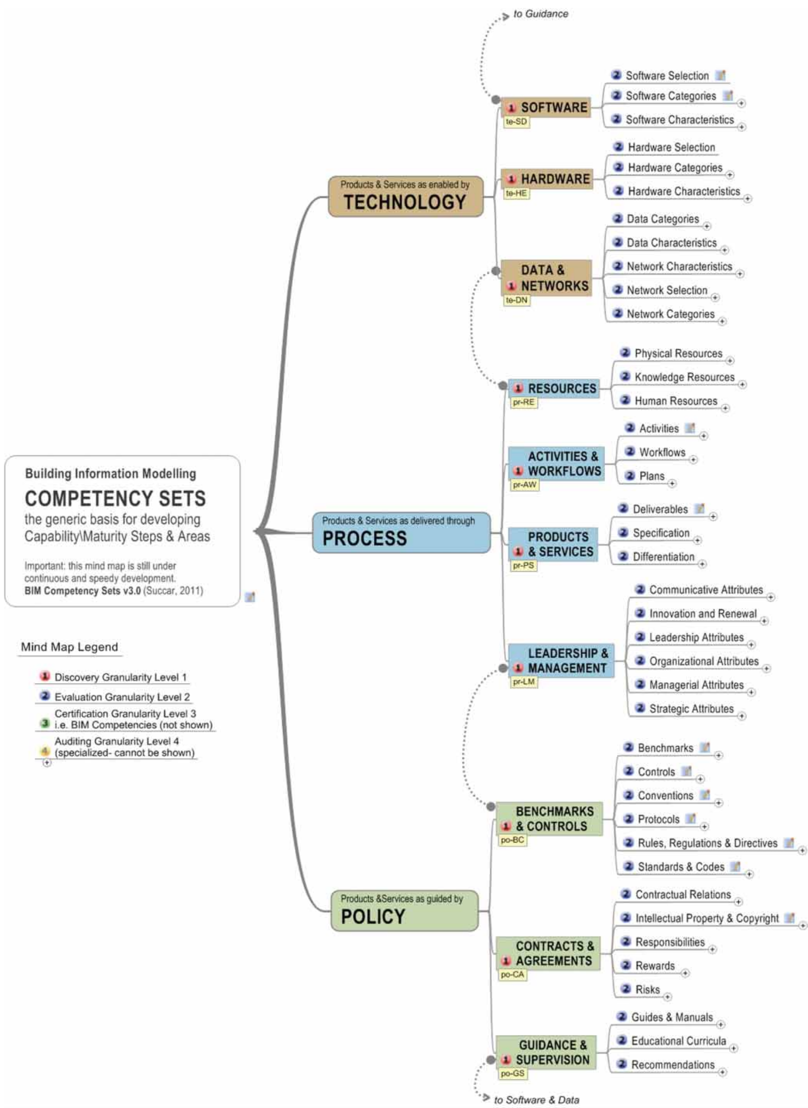


FIGURE 6 BIM Competency sets v3.0 – shown at Granularity Level 2

opportunities for DCO stakeholders to measure and improve their BIM performance. The components complement each other and enable highly targeted yet flexible performance analyses to be conducted. These range from informal self-assessments to highly detailed and formal organizational audits. Such a system of assessment can be used to standardize BIM implementation and assessment

TABLE 3 Organizational scales

LOW DETAIL			HIGH DETAIL			
NAME	SYM	GRANULARITY	NAME	SYM	GRANULARITY	SHORT DEFINITION
MACRO markets and industries	M	Markets 1	(Macro M)	M	Market 1	Markets are the 'world of commercial activity where goods and services are bought and sold'. http://bit.ly/pjB3c
			(Meso M)	Md	Defined market 2	Defined markets can be geographical, geopolitical or resultant from multi-party agreements similar to NAFTA or ASIAN
			(Micro M)	Ms	Sub-market 3	Sub-markets can be local or regional.
	I	Industries 4	(Macro I)	I	Industry 4	Industries are the *organized action of making of goods and services for sale*. Industries can traverse markets and may be service, product or project-based. The AEC industry is mostly Project-Based. http://bit.ly/ielY3
			(Meso I)	Is	Sector 5	A sector is a 'distinct subset of a market, society, industry, or economy whose components share similar characteristics' http://bit.ly/15UkZD
			(Micro I)	Id	Discipline 6	Disciplines are industry sectors, 'branches of knowledge, systems of rules of conduct or methods of practice'. http://bit.ly/7jT82
				Isp	Specialty 7	Specialty is a focus area of knowledge, expertise, production or service within a sub-discipline
MESO projects and their teams	P	Project teams 8	n/a	P	Project team 8	Project teams are temporary groupings of organizations with the aim of fulfilling predefined objectives of a project – a planned endeavour, usually with a specific goal and accomplished in several steps or stages. http://bit.ly/dqMYg
MICRO organizations units, their groups and members	O	Organizations 9	(Macro O)	O	Organization 9	An organization is a 'social arrangement which pursues collective goals, which controls its own performance, and which has a boundary separating it from its environment'. http://bit.ly/v7p9N
			(Meso O)	Ou	Organizational unit 10	Departments and units are specialized divisions of an organization. These can be co-located or distributed geographically
				Og	Organizational group (or team) 11	Organizational Groups consist of individual human resources assigned to perform an activity or deliver a set of assigned objectives. Groups (also referred to as organizational teams) can be physically co-located or formed across geographical or departmental lines
			(Micro O)	Om	Organizational member 12	Organizational members can be part of multiple organizational groups.

TABLE 4 BIM competency Granularity Levels v2.1

GLEVEL NUMBER, GLEVEL NAME, DESCRIPTION AND SCORING SYSTEM (NUMERICAL AND/OR NAMED)			OSCALE APPLICABILITY	ASSESSMENT BY, REPORT TYPE AND *GUIDE NAME*	
1	Discovery	A low detail assessment used for basic and semi-formal discovery of BIM capability and maturity. Discovery assessments yield a basic numerical score	All scales	Self	Discovery notes *BIMC&M discovery guide*
2	Evaluation	A more detailed assessment of BIM capability and maturity. Evaluation assessments yield a detailed numerical score	All scales	Self and peer	Evaluation sheets *BIMC&M evaluation guide*
3	Certification	A highly detailed appraisal of those competency areas applicable across disciplines, markets and sectors. Certification appraisal is used for structured (staged) capability and maturity and yields a formal, named maturity level	8 and 9	External consultant	Certificate *BIMC&M certification guide*
4	Auditing	Auditing is the most comprehensive appraisal type. In addition to competencies covered under certification, auditing appraises detailed competency areas including those specific to a market, discipline or a sector. Audits are highly customizable, suitable for non-structured (continuous) capability and maturity and yield a named maturity level plus a numerical maturity score for each competency area audited	8, 9, 10 and 11	Self, peer and external consultant	Audit report *BIMC&M auditing guide*

efforts, enable a structured approach to BIM education and training as well as establish a solid base for a formal BIM certification process.

After scrutiny of a significant part of the BIM framework through peer-reviewed publications and a series of international focus groups, the five

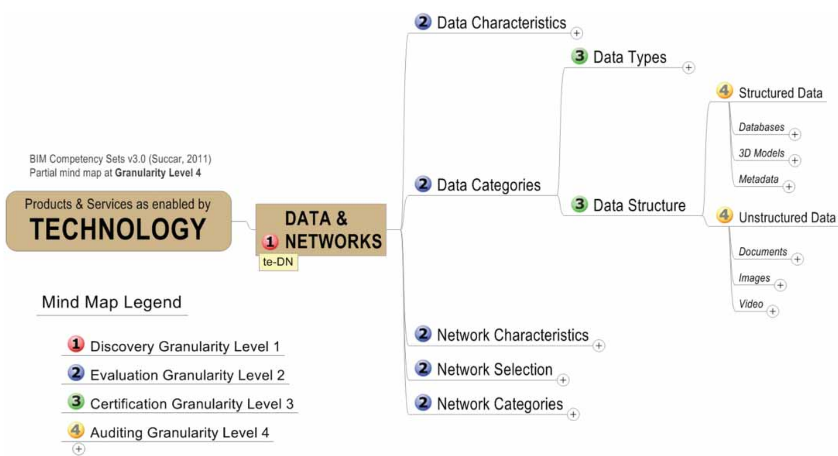


FIGURE 7 Technology competency areas at Granularity Level 4 – partial mind map v3.0

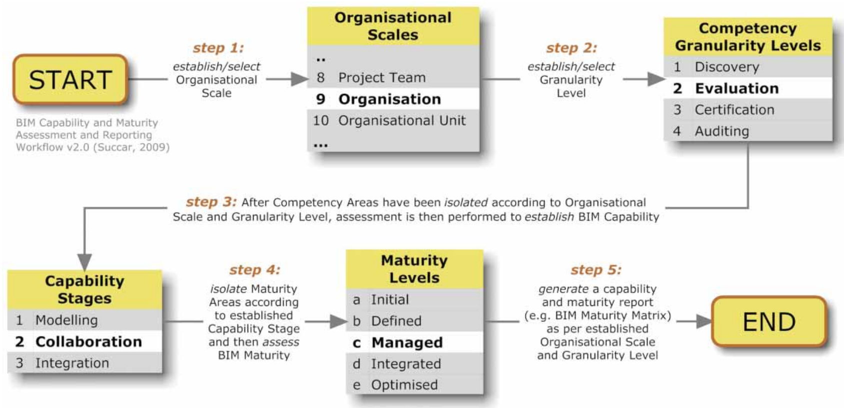


FIGURE 8 BIM capability and maturity assessment and reporting workflow diagram – v2.0

components and other related assessment metrics are currently being extended and field tested. Sample online tools (focusing on selected disciplines, at different granularities) are currently being formulated. All these form part of an ongoing effort to promote the establishment of an independent BIM certification body responsible for assessing and accrediting individuals, organizations and collaborative project teams. Subject to additional field testing and tool calibration, the five components may be well placed to consistently assess, and by extension improve, BIM performance.

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PAPER A6

An integrated approach to BIM competency acquisition, assessment and application

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An integrated approach to BIM competency assessment, acquisition and application

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ABSTRACT

Professional, organisational and educational institutions have started to adopt BIM software tools and adapt their existing delivery systems to satisfy evolving market requirements. To enable individuals within these organisations to develop their BIM abilities, it is important to identify the BIM competencies that need to be learned, applied on the job, and measured for the purposes of performance improvement. Expanding upon previous research, this paper focuses on *individual BIM competencies*, the building blocks of organisational capability. The paper first introduces several taxonomies and conceptual models to clarify how individual competencies may be *filtered*, *classified*, and *aggregated into a seed competency inventory*. Competency items are then fed into a specialised *knowledge engine* to generate flexible assessment tools, learning modules and process workflows. Finally, the paper discusses the many benefits this competency-based approach brings to industry and academia, and explores future conceptual and tool development efforts to enable industry-wide BIM performance assessment and improvement.

1. Introduction

Individual competencies are the fundamental building blocks of organisational competency. As such they represent a common set of standards that can be used for human resource planning, management, and development [52,57,35]. Individual competencies are crucial for managing the performance of an organisation [22], and according to Sanchez and Levine [76], the "same set of competencies normally cuts across jobs and layers of the organisation" and thus can be identified and analysed irrespective of organisational departments and units.

Recent efforts to identify individual competencies within the construction industry have focused on design [16], maintenance management [13], and construction project management [19]. These investigations and our previous research on BIM capability maturity [81,84], highlight the need for a comprehensive approach that identifies, classifies and maintains an inventory of generic BIM competencies *required for* modelling, collaboration and integration activities and *applicable across* project lifecycles, industry sectors, disciplines and specialities.

Identifying and then organizing generic competencies will not only facilitate BIM adoption but will also clarify the complex activities undertaken during multidisciplinary collaboration. Many of these activities (e.g. model interchange) require input from different project participants in a mutually interdependent manner. This mutual interdependence [85] is the "most costly way to coordinate, since the people performing the work need to communicate frequently and make mutual adjustments during task execution" ([51], page 514). To reduce the costs and inefficiencies of such mutual adjustments, Lavikka et al. ([51], page 519) strongly recommends task standardisation through defining "both the independently performed work tasks and the reciprocally interdependent tasks". Standardising and thus clarifying how BIM competencies are defined and organized should contribute significantly to reducing inefficient interdependencies between teams and organisations.

Previous research conducted by the authors has focused on organisational BIM capability and maturity. Several taxonomies and models were generated to clarify performance benchmarks including a multi-stage BIM capability model, a 5-level BIM maturity index and a 12-scale organisational hierarchy [80,81]. BIM competency sets – as applicable to organisations and teams – were also identified to enable BIM performance assessment and improvement [82,83]. Given that organisational capability/maturity and individual competency are interrelated and *can be combined* to analyse performance [32], it is first important to identify the different units of analysis at which competency can be assessed and suitably analysed.

2. Individuals as agents

The competency of *individual* actors within an organisational setting is the fundamental blocks of an *organisation*'s capability [52,23]. While the term *individual* represents intelligent human actors capable of coordinating defined processes with each other ([30] — page 19), the term *organisation* is less clearly delineated and is subject to intense theoretical debate [4]. Through metaphors, Morgan [64] describes organisations as machines; organisms; brains; cultures;

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political systems; psychic prisons; flux and transformation; and instruments of domination. Each of these metaphors includes its own characterisation of individual roles and their relationships with the organisation. In addition to metaphors, organisations can also be defined in terms of goals, roles and their dependencies [29] where individuals' roles are understood as a reflection of organisational goals.

In this paper, an organisation is defined as a "structural relationship between a collection of agents" ([27] — page 129). We see organisations as multi-agent systems where "the characteristics of the whole (the organisation) are defined in terms of the characteristics of the parts (e.g. persons), while the characteristics of the whole in turn influence the characteristics of the parts" ([30] — page 19). As an *assemblage of agents* (both human and non-human) and their interactions [30,43], an organisation includes "actors, responsibilities, dependencies, social structures, organisational entities, objectives, tasks and resources" ([29] — page 10).

An organisation's capability as a multi-agent system can thus be understood through the capabilities of its agents. The individual competencies of human agents, acting interdependently to achieve *coordinated goals* ([28] — page 2) thus not only mirrors the characteristics of the human agents themselves but also reflects the capability of the organisation within which these agents interact.

Through this understanding of individuals, organisations and their relationship, the next section delineates individual competencies and introduces a structure for their identification, classification and analysis.

2.1. Competency units of analysis

An individual is the basic or primary 'unit of analysis' in understanding organisational performance [52,86]. However, there are other *units* that can be analysed to identify and predict organisational performance. These units are presented below but are preceded by definitions of a number of terms that are often used interchangeably:

A. Competency, capability and maturity
Competency refers to an *individual's ability* to perform a specific task or deliver a measureable outcome. Both capability and maturity refer to *organisational abilities* across *organisational scales* [81]: capability denotes the *minimum ability* in performing a task or delivering a measureable outcome; maturity denotes the quality, repeatability and degree of excellence within a capability.

B. Groups and teams
A *group*, as a unit of competency analysis, is a *cluster of individuals* not bound together by a project or a set of performance goals [46]. Their performance is 'additive, the sum of individual work contributions' ([68] — page 328). Committees, communities of practice, councils and ad-hoc assemblies of people are good examples of groups. A *team* is a purposeful collective of individuals "who exist to perform organisationally relevant tasks, share one or more common goals, interact socially, exhibit task interdependencies, maintain and manage boundaries, and are embedded in an organisational context…" ([48, page 6] as mentioned in [59]). Team performance is 'synergistic, the product of inter-activity among the roles' ([68] — page 328). For the purposes of this research, we have extended the term 'team' to include – in addition to individuals – a *purposeful cluster* of organisations, temporarily bound together through a unifying long-term mission or a common goal/outcome.

These distinctions allow the introduction of several *units of analysis*, each with its own measure of competency/capability:

1. Individual competency is the unit measure of an individual's ability to conduct an activity and deliver an outcome. Individual competency applies to a *single person* irrespective of role, position or employment status;
2. Group competency is the arithmetic sum of several individual competencies but – as a measure – does not reflect the efficiencies gained or lost from such an aggregation;
3. Organisational capability is the unit measure of an organisation's ability and its sub-organisational units (branches, departments, business streams, etc.); and
4. Team capability is the unit measure of team members' combined abilities. As opposed to group competency, team capability reflects the routines and dynamics [74,37] of aggregation (e.g. team compatibility, communication and collaboration). There are at least[1] three sub-units of team capability.

   4.1. Work team capability applies to a purposeful group of individuals working together to deliver a project/outcome *within* an organisation or an organisational unit;
   4.2. Project team capability applies to a purposeful group of individuals working together to deliver a project/outcome *across* two or more organisations; and
   4.3. Organisational team capability applies to two or more organisations working together (through partnering, alliancing, etc.) to pursue a common mission or deliver a common project/outcome.

These competency units and sub-units are complementary and can be flexibly used to isolate, or aggregate, the abilities of individuals and organisations. Fig. 1 and Table 1 clarify the interdependent relationship between these units of analysis.

The units of analysis shown in Fig. 1 and Table 1 provide examples of the granularity of organisational performance. As noted by Dainty et al. [19], Kakabadase [45] states that there is a demonstrable link between the competency of team members and the overall performance of an organisation. Also, Salvato [73] has shown how the evolution of organisational capability is influenced by the 'ordinary' work activities of individuals within it.

Organisations do not typically assign work activities directly to an individual but to a team. However, a team is composed of individuals and to develop a team's capability each team member needs to "be developed so that they can contribute critical capabilities to the team. This requires the identification of the critical skills that are needed to make the team effective and the development of a learning program for individuals so that they can contribute to their team's effectiveness" ([52], page 8). Competency provides a "starting point to bridge individual and organisational levels of analysis" ([74] — page 474). To establish organisational performance, it is therefore important to establish the performance of individuals who, in turn, form teams. How individual competencies, as a measure of individual performance, are defined will underpin the performance assessment and improvement of all other units of analysis.

2.2. Individual competency — definitions

It is important to first acknowledge that there is no consensus among researchers on the meaning of the term *competency* [89,77,35]. According to Ley and Albert [53], "although competencies have been considered increasingly important in HR and KM approaches, it is thus far an unresolved issue of what exactly competencies are". Table 2 explores some of the different meanings attributed to the term competency/competencies[2] as applied to individuals within an organisational context.

[1] There are other types of teams that can be identified for the purposes of competency analysis similar to role teams (e.g. managerial team), activity teams (e.g. digging team) and recreational teams (e.g. a company' sports' team). However, only the three identified sub-units are of direct relevance to this research.

[2] This paper steers away from the semantic separation between competency/competence and competencies/competences [89,77,75].

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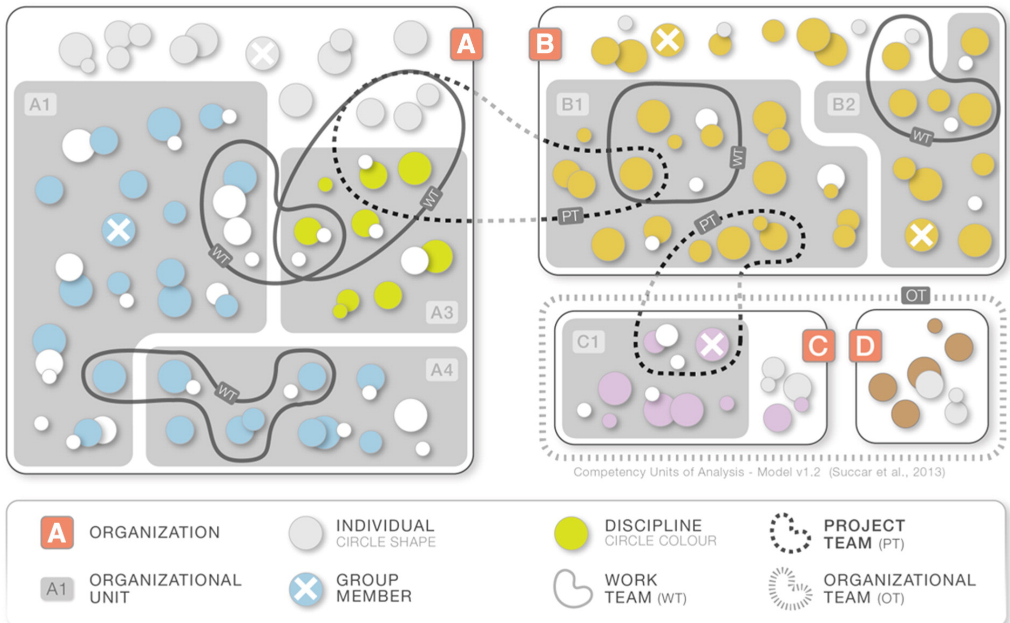

Fig. 1. Units of analysis — knowledge model identifying the units and sub-units.

Table 2 provides some of the many definitions published in academic and industrial literature. The variety of definitions reflects a multitude of meanings which – although not perfectly aligned – complement each other. To allow an integrated definition of individual BIM competency to be developed, custom classifications have been used to deconstruct the term competency. These will be re-assembled later to facilitate the classification of BIM competencies, the development of a BIM competency inventory and the introduction of a conceptual model for assessing, acquiring and applying BIM competencies.

2.3. Competency approaches

Table 2 reveals two general and complementary approaches to understanding the term competency when applied to individuals. The first approach identifies competency as an aggregation of *underlying, inner human qualities* leading to observable performance outcomes. This reflects the traditional understanding of competency prevalent within the fields of human resource management and skill/competency management — an understanding influenced by a long tradition in the field of psychology [53,60]. The second approach focuses less on personal traits and more on an individual's *professional* and *technical capabilities* as a measure to predict future performance. A competency is thus a combination of knowledge, skill and experience required to fulfil a specific task [67,88].

2.4. Competency components

Competency may be understood by analysing its component parts; the active ingredients that act in unison to deliver a measureable outcome yet can be isolated for focused inspection. As can be deduced from Table 2, an individual's abilities are the *aggregate sum of three components* — knowledge, skill and personal traits:

A. Knowledge: conceptual or theoretical knowledge [87];
B. Skill: procedural or applied knowledge [20]; and
C. Personal traits: the “other deployment-related characteristic (e.g. attitude, behaviour, physical ability)” ([38], page 5).

Competency components are complementary and may be used to define individual competencies. The relative significance of the three components/ingredients is not constant but varies to reflect the unique requirements of each measurable competency. For example, some individual competencies are based on substantial conceptual knowledge; while others are based on substantial practical skill. Some competencies require specific personal traits (including friendliness, empathy, dedication…) while other competencies may not require the same traits.

2.5. Competency manifestations

In applying the term competency to *describe*, *assess* and *predict* individual performance, three different competency manifestations can be isolated. These are as follows:

A. An individual competency as an *ability* – inert or learned – required to perform a defined activity or deliver a measureable outcome. This is exemplified in role definitions and position descriptions in advertisements which include a set of competencies *expressed as abilities or requirements.*
B. Individual competency as an *activity* – a set of tasks – performed for the purpose of delivering a measureable outcome. A step-by-step guide is a typical example of competencies *expressed as activities*; where individuals demonstrate their abilities by fulfilling an activity or a task.
C. Individual competency as an *outcome* or measureable deliverable — be it a product or a service. Learning outcomes from formal education or structured training are examples of competencies *expressed as outcomes or deliverables.*

As an example of a competency consistently applicable across the three manifestations, “using a 3D model to perform thermal analysis of a space” can be expressed as (i) a measure of an individual's *ability*

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Table 1
Units of analysis — matrix.

	Competency (individual abilities)	Capability (organisational abilities)	Maturity (organisational excellence)
Individual	Individual competency		
Organisational		Organisation capability	Organisational maturity
Group (ad-hoc collection of individuals)	Group competency (aggregate of individual competency)		
Work team (Purposeful cluster of individuals within an organisation)	Work team competency (Aggregate + dynamics of individual competency)		
Project team (Purposeful cluster of individuals across two or more organisations)	Project team competency (Aggregate + dynamics of individual competency)		
Organisational team (Purposeful cluster of organisations)		Org team capability (Aggregate + dynamics of organisational capability)	Org team maturity (Aggregate + dynamics of organisational maturity)

to use 3D models to perform thermal analysis; (ii) a *task/assignment* to use 3D models to perform thermal analysis; and (iii) a learning *outcome* based on education/training on how to use 3D models to perform thermal analysis.

2.6. Competency levels

An individual's competency cannot always be designated through a binary proposition (i.e. competent/incompetent) but may be better described as a continuum separating two poles: one representing *incompetence* – lack of relevant abilities – and *competence*, the abundance of relevant abilities. In between these two poles are several *competence increments* which can be used for the purposes of measurement and comparison. The Individual Competency Index (ICI) is a simplified version of the performance model developed by Benner ([9], pages 13–34) [32] and includes five distinct levels (Fig. 2):

- Level 0 (*none*) denotes a lack of competence in a specific area or topic;
- Level 1 (*basic*) denotes an understanding of fundamentals and some initial practical application;
- Level 2 (*intermediate*) denotes a solid conceptual understanding and some practical application;
- *Level 3* (advanced) denotes significant conceptual knowledge and practical experience in performing a competency to a consistently high standard; and
- Level 4 (expert) denotes extensive knowledge, refined skill and prolonged experience in performing a defined competency at the highest standard.

Table 2
Individual competency: a non-exhaustive list of available definitions.

Competencies as	Definition	Reference
Behavioural goals	Competencies are behavioural goals defined by organisational leaders – based on business strategy and organisational culture – to guide employees, achieve synergy, improve performance and generate consistent results	[42]
Capability to perform	Competency is a "combination of skills, abilities, and knowledge needed to perform a specific task"	([67], page 1)
	Competencies are a combination of tacit and explicit knowledge, behaviour and skills, that give someone the potential for effectiveness in task performance	[23]
	Competency is an "ability to perform tasks, business processes, job, core business, activities, practices applying human/physical/ICT resources (e.g. personnel knowledge, skills, attitude, as well as organisation machinery) aimed at offering products and/or services in the market"	([26], page 135)
	Competencies are those characteristics - knowledge, skills, mindsets, thought patterns, and the like-that, when used either singularly or in various combinations, result in successful performance	[24]
	A competency is "a knowledge, skill, ability, or characteristic associated with high performance on a job, such as problem solving, analytical thinking, or leadership"	([63], page 75)
	Competencies are "distinguishable elements of underlying capacities or potentials which allow job incumbents to act competently in certain situations"	[10] as translated from German by [53]
	A competency is "a specific, identifiable, definable, and measurable knowledge, skill, ability and/or other deployment-related characteristic (e.g. attitude, behaviour, physical ability) which a human resource may possess and which is necessary for, or material to, the performance of an activity within a specific business context"	([38], page 5)
	Competencies are measurable human capabilities that are required for effective work performance demands	[58]
Performance standards	Competencies are performance standards - the ability to perform to the standards required within employment	[34]
Standardized performance requirements	A competency is "a standardized requirement for an individual to properly perform a specific job and it encompasses a combination of skills, knowledge, and behaviour utilized to improve performance"	[14] as noted in ([2], page 1271)
Resources used to reach an objective	Competencies are the "effect of combining and implementing *Resources* in a specific *Context* (including physical, social, organisational, cultural and/or economical aspects) for reaching an *Objective* (or fulfilling a mission)"	([87], page 633)
A contextual expression of ability	A competency is a "way to put in practice some knowledge, know-how and also attitudes, inside a specific context"	([11], page 154)

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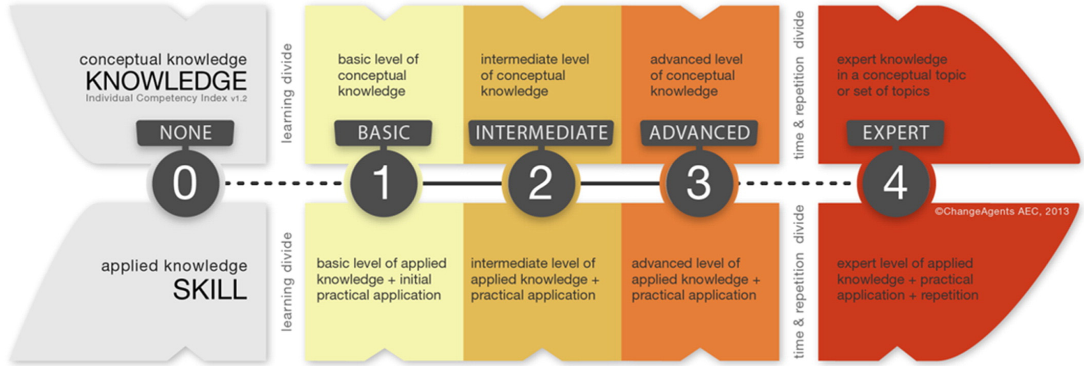

Fig. 2. The Individual Competency Index (ICI).

The ICI measures both the knowledge (conceptual knowledge) and skill (procedural knowledge) individuals require to perform a defined activity or deliver a measureable outcome. As a competency scale,[3] the ICI helps "establish the importance of a particular competency for a job, the proficiency level for each competency, and the competency level of an individual" ([63], page 76). The index also identifies two *competency divides*: the *learning divide* separating level 0 from level 1, and the *time/repetition divide* separating level 3 from level 4.

However, since ICIs only measures the abilities of *individuals* – and by extension, the aggregate abilities of a *group* of individuals – other indices are needed to establish the competencies of different organisational units. For example, BIM capability stages (Fig. 3) and BIM maturity index (Fig. 4) are sample complementary metrics which may be used to measure the BIM capability maturity of organisations, teams and other macro organisational scales [81].

3. Frequency, criticality and other competency labels

Competency frequency is a *measure of repetitiveness* and refers to "how often a competency is used in a particular job or group of jobs" ([63], page 75). Depending on the type of competency being classified, frequency can be reported in *quantitative* – e.g. three data exchanges every week – or *qualitative* terms — e.g. high frequency, medium frequency and low frequency. Competency criticality is a measure "of how important a particular competency is for a job or group of jobs" ([63], page 75). The criticality of a defined competency can be measured in *absolute* (using a 5-level Likert scale or similar) or *relative* terms (e.g. delivering learning outcome A is *less critical* than learning outcome C).

In addition to the above, there are many other criteria for classifying competencies, including autonomy, detail, evidence, specialty, complexity, context and priority. Competencies can also be classified using specialized *ontologies* [36,22] or applicable *standards* [40,39]. All these classifications can be applied *concurrently* or in *isolation* to organize competencies for use in assessment, implementation and learning systems.

[3] The ICI measures 2 out of 3 competency components (knowledge and skill). The third component (personal traits) requires specialized psychometric indices similar to Myers-Briggs [70] and RIASEC [3].

4. Individual BIM competencies

As introduced in the previous section, it is quite "impossible to arrive at a definition capable of accommodating and reconciling all the different ways that the term is used" ([89], page 12) [25]. However, we propose an *integrated definition* of individual BIM competencies which acknowledges and aligns many of these variations.

> Individual BIM competencies are the personal traits, professional knowledge and technical abilities required by an individual to perform a BIM activity or deliver a BIM-related outcome. These abilities, activities or outcomes must be measureable against performance standards and can be acquired or improved through education, training and/or development.

Some aspects of this integrated definition require clarification. These include:

1. Individual BIM competencies — these relate specifically to the *abilities of individuals* (and not to the competencies of groups, organisations or teams). Individuals can be professionals, tradespeople, academics or students from any discipline or specialty and irrespective of their position or role.
2. A BIM activity is a set of tasks directly related to procuring, generating, using, supporting and maintaining BIM-specific deliverables (as products and/or services). These deliverables typically include 3D models, documents and data required for designing, constructing and operating a facility throughout its lifecycle.
3. BIM competencies – like other competencies – *must be measureable* against performance standards. In some cases, the measurement is a simple *binary proposition*: does the ability to perform a BIM activity *exist* or *not*? In others, the measurement is a multilevel graduation: is the ability at a basic, intermediate or advanced level? Also, in some cases, competencies are objectively measured; while in others, they can only be subjectively recognized [38].
4. BIM competencies vary in their nature and *can be acquired* through equally varied means. This variety is a function of the competency itself and the individual seeking to acquire that competency. Our integrated definition does not differentiate between BIM competencies based on how they are acquired but includes competencies attained through:
   a. *Formal education* – with or without qualifications – typically focused on improving theoretical knowledge (e.g. learning design theory or how to calculate thermal gain);

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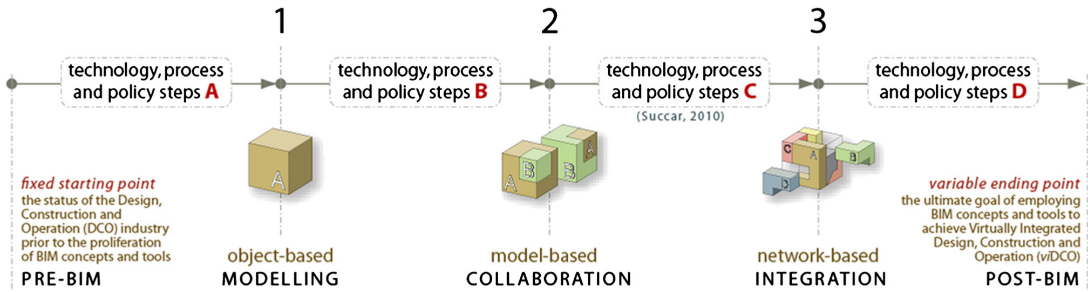

Fig. 3. BIM capability stages — shown at maturity level c.

b. *Vocational or on-the-job training* typically focused on skill improvement (e.g. how to use Autodesk Revit or operate a laser scanner); or
c. *Professional development* typically focused on improving personal traits (including self-confidence and critical thinking).

This integrated definition aligns many of the meanings attributed to the term 'competency', as reflected in Fig. 5. This illustrates the manner in which competencies may be seen to flow from *identification*, to *classification*, to *aggregation* and finally to *use*.

5. BIM competency identification

Numerous recent peer-reviewed research and industry publications have focussed on model-based deliverables and their diverse technical, procedural and regulatory criteria. With the exception of some investigations that address emerging *BIM roles* [8,7,78,66], and identify competencies related to a small number of specialties [16,13,19], comprehensive research on overall BIM competency is yet to be published.

Identifying a set of BIM-specific roles (including BIM manager, model manager and lead BIM coordinator) is a useful exercise for recruitment purposes; however, these role definitions are bound to rapidly change to reflect the relentless technological and procedural transformations from which the roles are derived.[4] Identifying the specific competency requirements of a discipline or specialty requires clarity about responsibilities. However, such an approach does not lend itself to identifying the BIM competencies common across specialties. Finally, the identification of BIM competencies specific to an organisation – the approach taken by specialist consultants – is useful for that organisation; however, it contributes little towards identifying competencies across the wider industry. A more pertinent and persistent approach would be to avoid rigid delimitation of BIM roles within arguably narrow contexts (within a specific organisation or required for a specific project) and to focus more intently on identifying industry-wide BIM competencies that shape current roles and affect emergent ones. The significance of this wider approach is amplified by the need to facilitate multidisciplinary collaboration, encourage integrated practices and workflows, and reduce inefficient interdependency [85,51] between teams and organisations.

The process of *industry-wide*, as opposed to role-, organisation-, or discipline-specific identification of BIM competencies, requires a multi-thronged approach. Competencies can be harvested from several sources: some are publically available and easily accessible, while others require much investigative and focused effort. There are several complementary ways to identify, refine and validate individual BIM competencies including:

1. Analysing 'job advertisement descriptions' crafted by recruitment sites;
2. Dissecting BIM-specific roles as defined within BIM guides, BIM management plans and similar documents;
3. Reviewing academic literature and industry publications focused on BIM workflows, deliverables and their requirements
4. Adopting and adapting formal skill inventories, competency pools, and accreditation criteria similar to those described by HR-XML-Consortium [38]; and
5. Harvesting competency requirements from industry associations, organisations and subject matter experts through interviews, focus groups and dedicated surveys.

In summary, there are many available resources, established methods and accessible means of identifying BIM competencies across the DCO industry. Through these multiple sources, BIM competencies can be *collected at an industrial scale*,[5] *conceptually filtered*[6] to isolate those which satisfy our integrated definition, and *classified* using a specially-developed, tiered taxonomy.

6. BIM competency classification — a tiered taxonomy

The number of competencies that can be collected and would satisfy the aforementioned integrated definition can be very large. To organize BIM competencies into useable clusters, a specialized taxonomy is needed.

Taxonomies are an efficient and effective way to organize and consolidate knowledge [90]. A well-structured taxonomy allows "the meaningful clustering of experience" ([50] — page 24) and is "a means toward a number of different ends; one of these ends is providing direction and/or guidance to expansion or generalisation of knowledge" ([91] — page 216). In developing a specialized taxonomy to organize BIM competencies, we have adopted the guidelines introduced by Gregor ([33], page 619): a taxonomy is expected to be "complete and exhaustive; [includes] classes that encompass all phenomena of interest; [is based on] decision rules, [which are] simple and parsimonious to assign instances to classes; and the classes should be mutually exclusive. In addition, as taxonomies are proposed to aid human understanding, [these classes should be] easily understood and […] appear natural."

The BIM competency hierarchy (Fig. 6) is a taxonomy organizing BIM competencies into meaningful, exhaustive, and mutually-exclusive clusters [33]. This clustering is goal-driven and aims to simplify a large system by decomposing it into smaller sub-systems [62] ([63], page 75). The hierarchy has several levels: competency tiers (top level) include all BIM competencies that satisfy the integrated definition introduced earlier;

[4] Mansfield [57] estimated that the shelf life of a role (or a competency model representing a role) is likely to be two years or less. This is arguably as true today as it was in the 1990s.

[5] For an exploration of Organizational Scales, please refer to ref. [81].
[6] For a discussion on conceptual lenses and filters, please refer to ref. [80].

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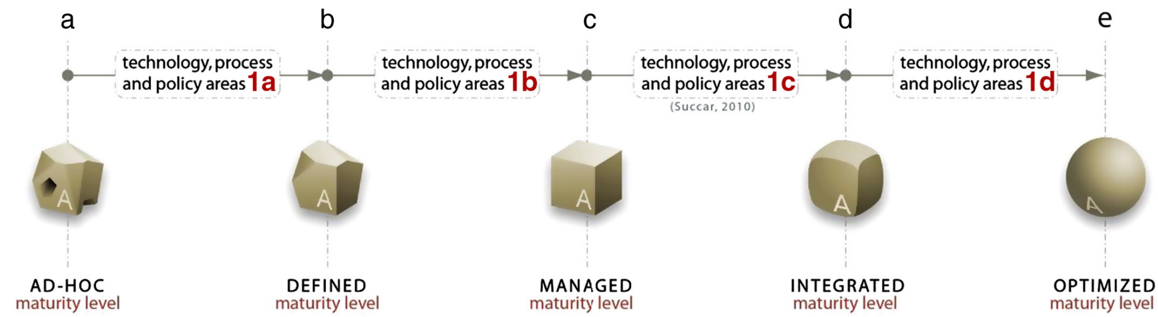

Fig. 4. The BIM Maturity Index (BIMMI) — shown at capability stage 1.

lower levels distribute competencies into competency sets and competency topics. The naming of clusters within tiers, sets and topics is based on literature and has been inferred inductively through observation and discovery [61].

Fig. 6 shows three BIM competency tiers divided into several BIM competency sets which are, in turn, subdivided into BIM competency topics. These tiers, sets, topics and their granular subdivisions (competency items) represent *all the measureable abilities, outcomes* and *activities* of individuals who deliver model-based products and services. Importantly, this representation of abilities accurately identifies an individual's competency profile using a broad spectrum of topics. It is driven by the notion that an individual cannot be recognized as either competent or incompetent *as a whole* but may be “an expert in one competency item due to their level of experience and theoretical knowledge, whilst at the same time being a novice in a competency of which they have no experience or background knowledge”([31] — page 154). Competency subdivisions are explored in detail below.

6.1. Tier 1: core competencies

The core competencies tier reflects the *personal abilities* of individuals enabling them to conduct a measureable activity or deliver a measurable outcome. This core tier is subdivided into the following four competency sets:

1. Foundational traits — personal attributes *inherent in an individual* that cannot be acquired through training or education. Foundational traits represent an individual's attitude, behaviour, motivation, and other attributes measureable through psychometric indices similar to Myers–Briggs Type Indicators [70], the RIASEC model [3] and other personality assessment systems. A natural affinity to learning new languages, or an innate ability to solve complex mathematical problems are examples of these traits;
2. Situational enablers — personal attributes related to nationality, language and other criteria which may play a *relevant* role when delivering a service or a product. For example, being of a specific nationality or having the ability to speak a certain language may be considered enablers in certain situations. Situational enablers are not absolute in nature; criteria considered relevant in one situation may be considered irrelevant in others;
3. Qualifications and licenses — personal attributes related to the *existence* or *sufficiency of* academic degrees, scientific publications, professional accreditations, trade/skill certificates or licences. Qualifications and licences are measureable and provide evidence to “substantiate the existence (sic), sufficiency, or level of a Competency” ([38], page 12); and
4. Historical indicators — attributes related to employment history, project experiences (including project types and sizes), roles played and positions held. Historical indicators provide verifiable information about past activities and indicate potential abilities in similar future situations. For example, a BIM manager's role played by an individual at an engineering company for a number of years is an indicator of specific competencies in engineering-specific BIM management.

The core competencies tier refers to *personal abilities* as opposed to ‘organisational core competences’. The collective capabilities embedded within an organisation form its competitive advantage, customer value, resistance to imitation and ability to grow — as advocated by [71]. However since organisational core competence is “dependent on and inextricably intertwined with individuals' job competence” ([54] — page 436) and typically represents the “competencies everyone in a company

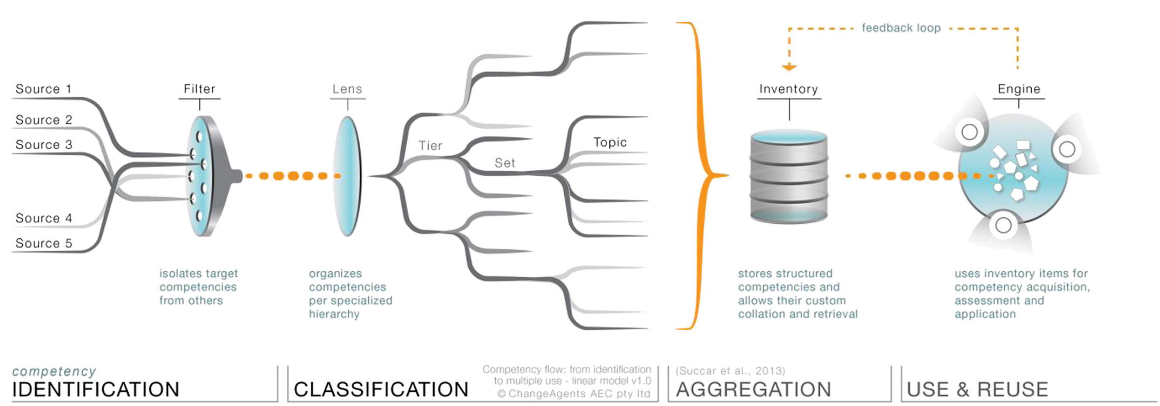

Fig. 5. Competency flow: from identification to multiple use.

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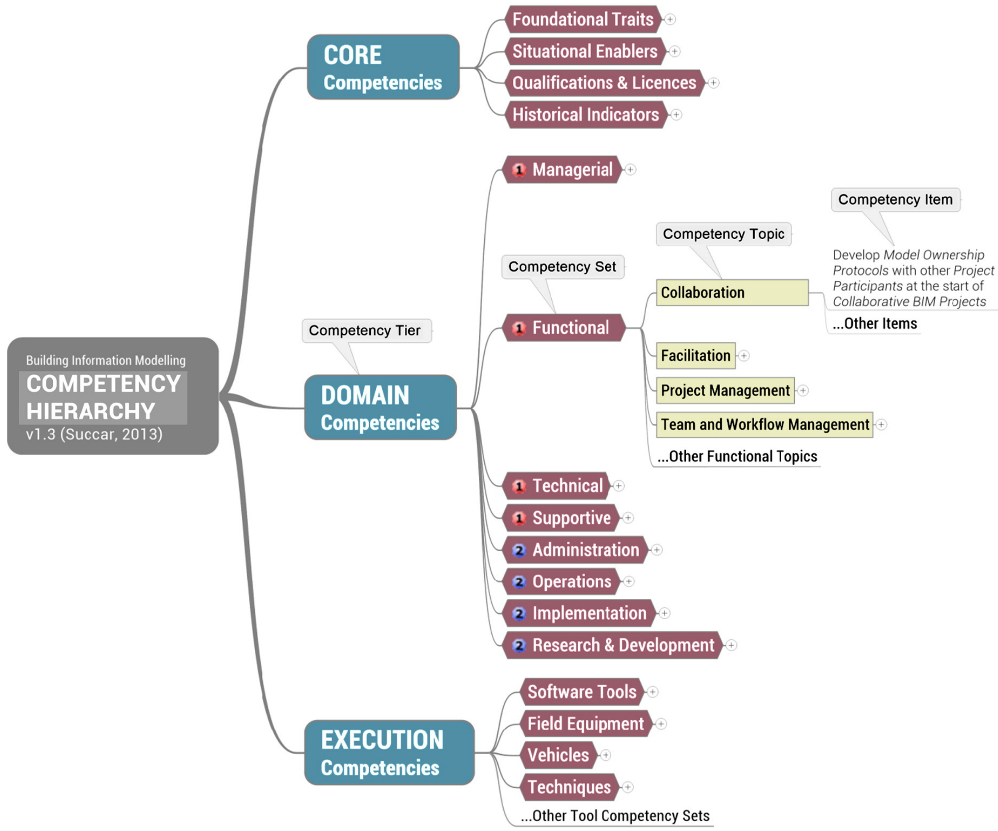

Fig. 6. BIM competency hierarchy — a multi-level taxonomy for organizing individual BIM competencies.

needs" ([53] — page 1510), individuals' core abilities form part of the organisation's core competence.

6.2. Tier 2: domain competencies

The domain competencies tier (Fig. 6) refers to the *professional abilities* of individuals, the *means* they use to perform multi-task activities and the *methods* they employ to deliver outcomes with complex requirements. There are eight competency sets within this tier: four primary sets (managerial, functional, technical and supportive) representing the main types of professional ability; and four secondary sets (administration, operation, implementation and research & development) identifying those abilities which are formed by the overlap of Primary Sets (Fig. 7):

1. *Primary competency sets* represent an individual's professional abilities distributed into the following four sets:
   a. *Managerial:* decision-making abilities which drive the selection/adoption of long-term strategies and initiatives. Managerial competencies include leadership, strategic planning and organisational management (e.g. '*the ability* to understand the Business Benefits and Business Risks of model-based workflows' is a *competency item* within the strategic planning *competency topic*, within the managerial *competency set*);
   b. *Functional:* the non-technical, overall abilities required to initiate, manage and deliver projects. Functional competencies include collaboration, facilitation, project management… (e.g. *the ability* to facilitate a multi-disciplinary BIM meeting);
   c. *Technical:* the individual abilities required to generate project deliverables across disciplines and specialities. Technical competencies include modelling, drafting, model management… (e.g. *the ability* to use BIM Software Tools to generate accurate, error-free models); and
   d. *Supportive:* these competencies are the abilities required to maintain information and communication technology (ICT) systems. They include ICT support, hardware maintenance, software troubleshooting… (e.g. *the ability* to assist others to troubleshoot basic software and hardware issues).
2. *Secondary competency sets* represents an individual's ancillary professional abilities. They include the following four sets:
   a. *Administration:* the activities required to fulfil and maintain organisational objectives. Administration competencies include tendering and procurement, contract management and human resource management (e.g. *the ability* to establish the necessary metrics to measure the financial performance of BIM projects);
   b. *Operation*: the practices and efforts required to deliver a project or part/aspect of a project. Operational competencies include designing, analysing, simulating and estimating (e.g. *the ability* to use models to generate bill(s) of quantities);
   c. *Implementation:* the activities required to introduce transformative concepts and tools (revolutionary or evolutionary) into an organisation. Implementation competencies include component

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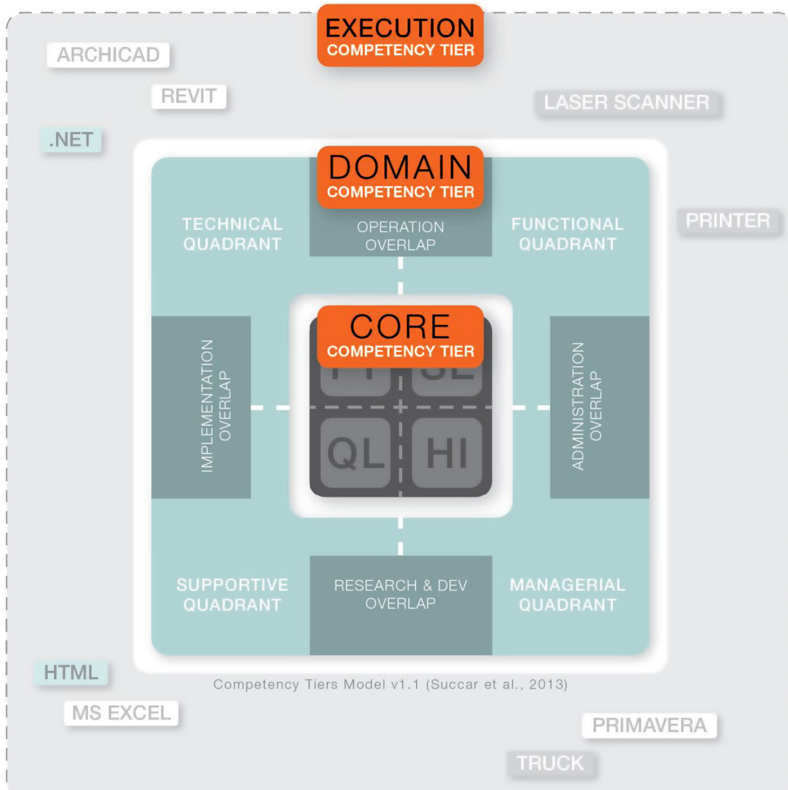

Fig. 7. Competencies tiers model.

development, library management and standardisation (e.g. *the ability* to develop protocols specific to generating and maintaining a Model Component Library); and

d. *Research and Development:* the activities required to evaluate existing processes, investigate new solutions and facilitate their adoption within the organisation or by the larger industry. Research and development competencies include change management, knowledge engineering, research and coaching (e.g. *the ability* to monitor, select and recommend technological solutions to enhance organisational workflows and deliverables).

6.3. Tier 3: execution competencies

The execution competencies tier (Fig. 6) represents an individual's ability to use specific *tools* and *techniques* to conduct an activity or deliver a measureable outcome. The ability to use a software tool (e.g. a 3D model authoring tool), drive a vehicle (e.g. a 30 tonne tipper truck) or operate specialized field equipment (e.g. a laser scanner) are examples of execution tier competencies. Also, the ability to employ specialized *techniques* (e.g. programming, drawing and plastering) is also classified under the Execution Competency Tier.

Competencies organized by tiers, sets and topics complement each other. That is, for an individual to deliver an activity, a mixture of competencies from across all three tiers is typically required. For example, for a structural engineer to efficiently generate and exchange a data-rich 3D model with an architect, she/he will require *core* engineering qualifications, BIM *domain* expertise (knowledge of collaboration requirements and data exchange protocols) and *execution* abilities (ability to use modelling and data exchange tools). Table 3 further clarifies how competencies complement each other from across different tiers, sets and topics:

In addition to the BIM competency hierarchy – the main skeleton around which BIM competencies are organized – auxiliary classifications criteria (competency labels) may concurrently apply. For example, competencies may be as labelled as *generic* or *specialized*. Generic BIM competencies are equally valid across all disciplines, specialties and roles; while *specialized* competencies are valid only within a subset of disciplines, specialties and roles:

- An *architect* (Discipline A) developing a 3D spatial model for a hospital building would require a *different set* of competencies from those required by an *engineer* (Discipline B) performing thermal analysis of the hospital's zones. However both individuals would need to *know how* to exchange data and communicate their respective requirements.
- The daily activities required from *a junior draftsperson* (Role A) engaged in generating 3D models or documents are not the same as those required by a *team manager* (Role B) responsible for coordinating the efforts of many individuals. However, both individuals would need to *know what* documentation and delivery standards to apply.

Irrespective of the labels used, classification is the meaningful clustering of experience [50]. Organizing BIM competencies in this manner allows for the meaningful aggregation of BIM knowledge, skill and experience into a structured inventory to be used for industry-wide performance assessment and improvement.

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Table 3
Competencies complement each other from across different tiers, sets and topics.

Core competencies Competency topic (Competency set)	Domain competencies Competency topic (Competency set)	Execution competencies Competency item (Competency set > competency topic)
Creativity (foundational traits)	Design conceptualisation (operations)	ArchiCAD (Software tools > model authoring)
Diploma e.g. dip in project management (Qualification and licences)	Project management (Functional)	Primavera (Software tools > project management)
Driving license (Qualification and licences)	[No complementary competency]	Car (Vehicles > transportation)
Curiosity (Foundational traits)	Research and analysis (Research and development)	Nvivo (Software tools > data analysis)
Time management (Foundational traits)	[No complementary competency]	Getting things done (GTD) (Techniques > organisation)
Market experience (Situational enablers)	[No complementary competency]	[No complementary competency]
Strategic mindset (Foundational traits)	Strategic planning (Managerial)	[No complementary competency]
[No complementary competency]	Web development (Supportive)	HTML (Techniques > programming)
Previous positions e.g. in management (Historical indicators)	General management (Managerial)	BPMN (Techniques > representation)

7. Generic BIM competencies — a seed inventory

There are arguably hundreds of *generic* BIM competencies common across disciplines, specialties and roles. There are also, depending on the level of detail used to define competencies, thousands of *specialized* BIM competencies reflecting the unique requirements of each discipline, specialty and role (e.g. structural engineers, ducting sub-contractors and site managers respectively). Table 4 introduces a seed inventory of *generic* BIM domain competencies and provides sample competency items for each of its eight competency sets:

The seed competency inventory (Table 4) includes sample competency items formulated using a standardized *sentence structure* and employing standardized *BIM terminology* (shown underlined). These BIM terms are part of a *BIM dictionary*, a discrete inventory developed to clarify the meaning of terms used within competency items. The dictionary eliminates conflicting definitions; identifies synonyms or term variations across markets; and allows competency items to be succinctly formulated. Most importantly, the BIM dictionary acts as a *web of meaning* [18] connecting terms to each other; to learning material; to knowledge bases; and to competency items which use them. Table 5 provides

Table 4
Seed BIM domain competency inventory.

Competency set	Competency topic (Partial)	Individual BIM Competency Item (Sample items at low-detail definition; expressed as activities)
Managerial	Leadership	Generate an overall mission statement covering BIM Implementation within an organisation
	Strategic planning	Define the strategic objectives to be achieved from implementing BIM software tools and model-based workflows
	Organisational management	Identify changes to organisational processes as necessary to benefit from model-based workflows
Administration	Administration, policies and procedures	Organize initiatives to encourage staff to adopt BIM software tools and workflows within the organisation
	finance, accounting and budgeting	Establish the necessary *metrics* to measure the financial performance of BIM projects
	Human resource management	Identify the responsibilities of a BIM manager, a model manager and similar BIM roles
Functional	Collaboration	Develop model ownership protocols with other project participants at/before the start of collaborative BIM projects
	Facilitation	Act as the project team's BIM facilitator during the delivery of collaborative BIM projects
	Team and workflow management	Use a content management system or a document management *system* to manage information storage and sharing
Operation	Designing and conceptualizing	Use a BIM software tool to generate a rough representation of a space through basic geometry and identify spatial relationships
	Analysing and simulating	Use specialized software tools to generate a thermal study from a data rich 3D model
	Quantifying and estimating	Prepare a BIModel for the purpose of linking it to a construction schedule
Technical	Modelling and drafting	Generate BIModels using a pre-defined set of standards and guidelines
	Documentation and detailing	Generate *2D Drawings* of an accuracy suitable for construction documentation and submittal for *Tender/Bid*
	Model management	Maintain a *BIModel* according to modelling standards set by the organisation or project team
Implementation	Implementation fundamentals	Compare different BIM software tools and select the one most suitable for an organisation
	Component development	Generate basic model components which comply with organisation's modelling standards
	Technical training	Develop a skill register, a training log or similar to track existing and newly acquired skills
Supportive	IT support	Conduct tests to establish whether IT systems are running at required levels of performance and stability
	Software and web development	Develop tools/extensions to improve the project deliverables of off-the-shelf BIM software tools
	software-related troubleshooting	Manage the relationship between an organisation and its BIM software tool vendor/reseller
Research and development	General R&D	Generate a BIM-specific R&D plan for an organisation
	Teaching and coaching	Develop a well-defined approach to identify change resistance or change saturation during the BIM implementation process
	Industry engagement and knowledge sharing	Develop non-technical educational material to assist staff in understanding the business and process requirements of BIM

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Table 5
Sample BIM dictionary terms and their BIM-specific definitions.

Terms (similar terms)	BIM specific definition	Further reading
Algorithmic model	A model generated using algorithmic functions manipulated by the end-user to explore design form or function. A typical use of Algorithmic Models is form-finding, where computational methods are used to drive shape generation, what-if scenarios and structural optimisation. While Algorithmic Models are a type of Parametric Models, they are not necessarily object-based and may only be loosely labelled as BIModels (e.g. Bentley's Generative Components is a software specialized in generating Algorithmic Models which can then be linked to BIModels).	[47]
Code checking and validation (Code validation; constraint checking; rule-based checking)	A process using a Specialized Software Tool to check for the compliance of model parameters against design, performance and/or safety codes.	[17]
Project complexity	Project complexity is measurement of how difficult a project is to design and construct. Project complexity is identified through a collection of variables which include site constraints, shape of structure, scale, scope, skill availability, cost constraints, legal framework, logistics, etc.	[12]

three sample BIM terms – out of hundreds needed[7] – and their BIM-specific definitions:

These standardized terms clarify BIM concepts, deliverables and their requirements across competency items, topics, sets and tiers. The semantic connectivity achieved by the BIM dictionary provides consistency and allows each competency item to be used in a variety of goal-driven and complementary ways.

8. BIM competency use — a sample model

There are several ways to benefit from the BIM domain competency inventory (Table 4) and its expansive list of structured competency items. The Triple A Competency Model (Fig. 8) is a *knowledge engine* [5,21] which uses structured BIM competency items to perform three complementary actions -competency acquisition, competency application and competency assessment. These actions are described below.

8.1. Competency acquisition

Competency acquisition is the *action referring to the process of learning* through competency items. This is achieved by purposefully collating BIM competency items into *BIM Learning Modules* to be used in professional development, vocational training and tertiary education. Using the many competency classifications and labels introduced earlier, learning modules – also referred to as *learning objects* [6] – can be formulated at an appropriate level of detail and fulfils the educational requirements of a target audience — be it an undergraduate student, a tradesperson, or a construction manager. Table 6 exemplifies how BIM competency sets and topics are used to generate sample BIM Learning Modules:

Competency items and topics can thus be used – when purposefully collated into BIM learning modules – for acquisition and improvement of individual knowledge and skill. According to Voorhees ([88], page 9), a "single competency can be used in many different ways […] The challenge is to determine which competencies can be bundled together to provide different types of learners with the optimal combination of skills and knowledge needed to perform a specific task".

8.2. Competency application

Competency application is *the action referring to the process of using* competency items to conduct an activity or deliver a measurable outcome. There are several approaches in *applying* structured BIM competencies - competency items can be used to:

1. Populate task lists for initiating projects and processes (e.g. a step-by-step guide for importing geometry drawn outside a Gehry Technologies Digital Project) or quality-checking project deliverables (e.g. a check list for auditing a model's quality);
2. Generate standardized mind maps, workflow diagrams and similar charts to clarify BIM implementation activities, data exchange and collaboration processes; and
3. Establish project requirements for the purposes of procuring services — e.g. through using competency items to populate a request for qualification or request for proposal.

Fig. 9 below illustrates how individual BIM competencies can be used to generate BIM workflows through a structured graphical language – shown here using Business Process Modelling Notation [65].

The partial workflow (Fig. 9) uses BIM competency items from across several Competency Sets to clarify a specific process — how to initiate a collaborative BIM project. The BPMN concepts are represented at *low detail* and can be expanded into several sub-processes populated with competency items at higher levels of detail.

8.3. Competency assessment

Competency assessment is an action *referring to the process of measuring* the abilities of individuals within both professional and academic settings. From an organisational perspective, individual competencies – knowledge, skill and personal traits – are the "most important resources of a company for solving knowledge-intensive tasks such as decision-making, strategic planning, or creative design" ([72], page 506). These individual competencies – of employees for example – may not be always explicit. Through assessment, the availability and extent of an employee's competency can be made explicit, rendering it "easier to find out what people know or to direct people to others who can be of help. This sharing of information improves the organisational productivity as well as the individual performance" ([72], page 507).

Fig. 10 below demonstrates how competency items can be used to measure Individual BIM competencies through a dedicated online assessment tool.[8] In this example, individuals have been asked to assess their own abilities using the 5-level BIM competency index.

Competency assessment not only facilitates HR management processes within organisational settings (e.g. HR selection, planning, and succession planning), but can also "help to predict project management performance against a range of key performance criteria" ([19], page 2). Structured competencies enable the generation of an assessment framework for competency-based learning that measures what learners know or can accomplish through precise descriptions [88].

[7] The BIM Dictionary has been implemented as a free online tool http://www.BIMexcellence.net/dictionary. (Developed by ChangeAgents AEC and released under a Creative Commons 3.0 license. The BIM Dictionary currently includes more than 330 interlinked BIM terms and their research-based definitions.

[8] The image shown is from BIMexcellence.net, individual discovery (Beta 1). Competency items shown are from the domain tier > functional set > collaboration topic.

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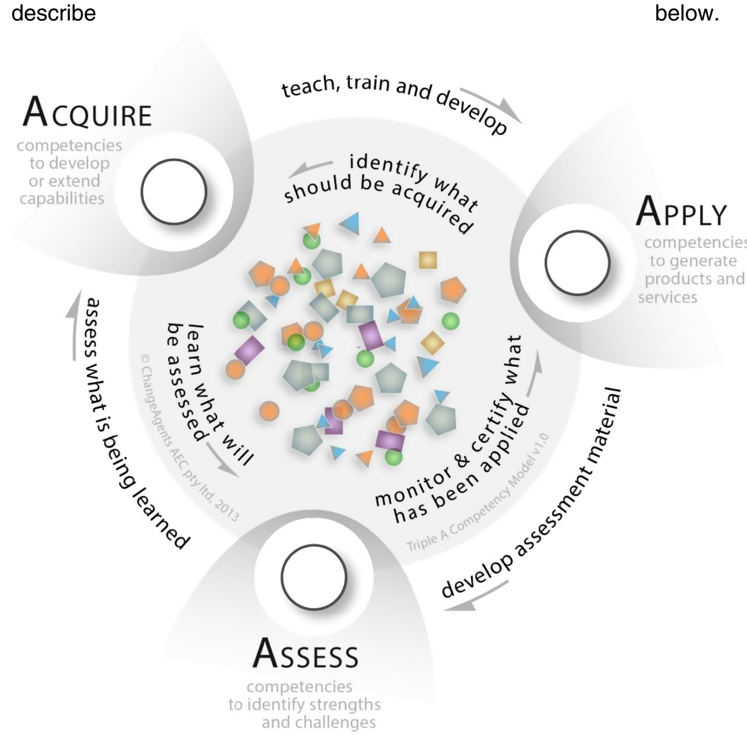

Fig. 8. The triple A competency model — coloured shapes denote discrete competency items. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

9. Three actions — multiple uses

The three actions introduced in the Triple A Competency Model (Fig. 7) have numerous applications when used in conjunction with structured BIM competencies. Depending on the competency syntax (i.e. *how* a competency item is worded) and its intended use, every item derived from the competency inventory (Table 4) can concurrently enable learning, assessment and practical application. Separating the syntax from the competency item – and thus not identifying competency items as *specific behavioural tasks* –

Table 6
BIM learning modules — formulated using BIM competency sets and topics.

Course, lecture or lesson	Learning modules (Competency tier > set > topic)	Discipline and sector (Target audience)	Delivery level (Delivery method)	Prerequisites
BIM basics	Introduction to building information modelling concepts (Domain > functional > functional basics) Autodesk revit — fundamentals (Execution > software tools > model authoring)	33 (code 33 denote all disciplines and roles, please refer to legend)	Level 1 (Video) Level 1 (Lab)	N/A
BIM legal	Contractual implications of using 3D models as a primary source of design information (Domain > administration > contract management)	33-21 (BIM managers, senior technical staff — design discipline)	Level 2 (Workshop)	All contract management topics at level 1
BIM project facilitation	Developing a BIM management plan (Domain > functional > facilitation) Understanding data exchange protocols (Domain > technical > data and networks) Understanding model progression specifications (Domain > technical > model management) Document management — general (Execution > web tools > document management)	33 (project managers, clients, facility managers)	Level 2 (Workshop) Level 2 (Presentation) Level 2 (Workshop) Level 1 (Presentation)	All functional set at level 1 + understanding data exchange protocols at level 2 All of technical set at level 1 N/A
Model management for collaborative projects	Understanding data exchange protocols (Domain > technical > data and networks) Model auditing for model managers (Domain > technical > model management)	33 (BIM managers, senior technical staff — all disciplines)	Level 2 (Online presentation) Level 3 (Lab)	All data and networks topics at level 1 All model management topics at levels 1 and 2

Legend:
Discipline and sector are based on OmniClass Table 33. OmniClass is an Open Standard developed by the Construction Specifications Institute (CSI) — http://www.omniclass.org/.
Delivery level is a classification applied to each BIM topic to indicate prerequisite levels of knowledge, skill, and experience (e.g. Delivery Level 1 topics focus on 'BIM awareness' and have no prerequisites).
Delivery method identifies the recommended format(s) for delivering a BIM topic to a target audience.

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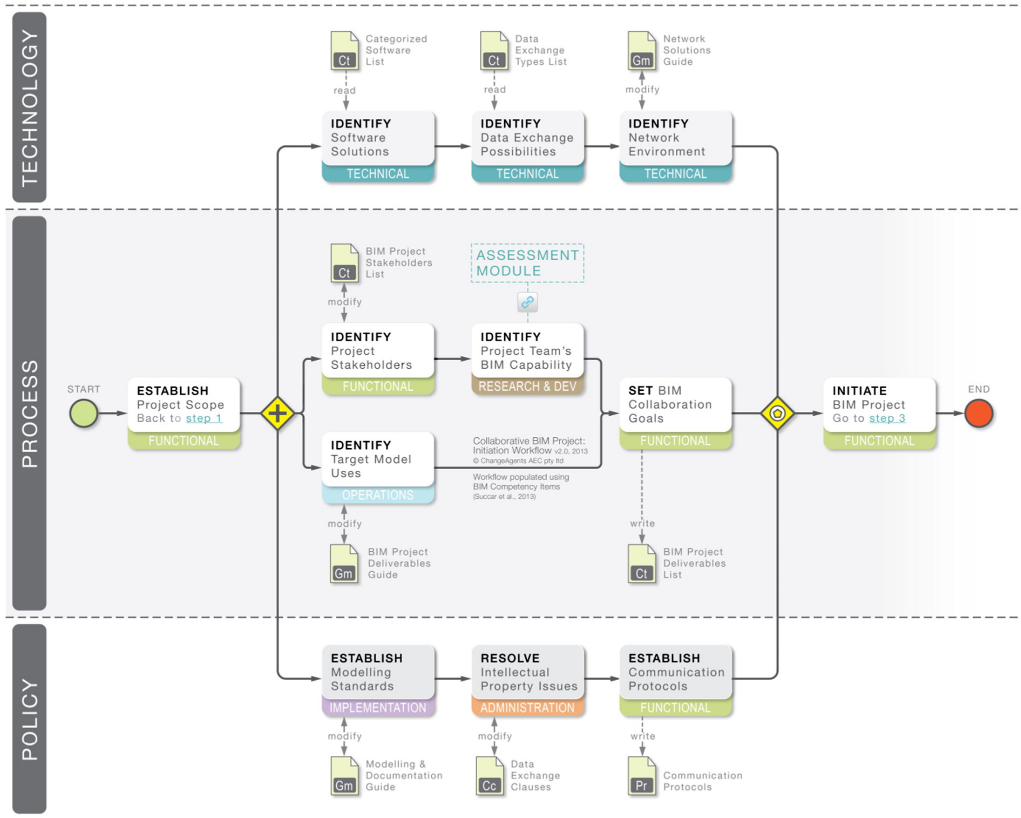

Fig. 9. Collaborative BIM project initiation workflow — v2.0.

provides the inventory with flexibility and adaptability ([32] page 783). Table 7 demonstrates how a sample competency item – *prepare a 3D model for the purpose of linking it to a construction schedule* – is *acted upon* to deliver multiple uses across several units of analysis.

Table 7 depicts how a sample competency item can be used for competency assessment, application and acquisition. Modifying the competency syntax to establish frequency, detail, evidence or priority would further qualify and extend the use and reuse of every item within the BIM competency inventory.

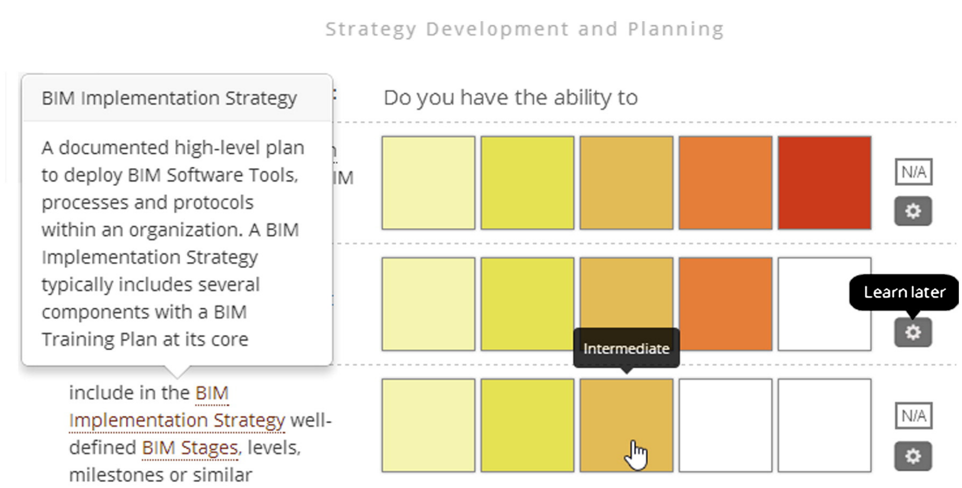

Fig. 10. Individual BIM competency assessment — *as applied in BIMexcellecne.net (beta 1).*

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Table 7
Sample competency item across actions, units of analysis, applications and measurements.

Action (More info)	Competency [syntax] "Competency item"	Unit of analysis (More info)	Intended use	Applicable metrics
Assess (The primary action for measuring the availability/level of competencies)	[Do you] [have the ability to] "*prepare a 3D model for the purpose of linking it to a* <u>*Construction Schedule*</u>"	Individual	Competency assessment	BIM**CI**
	[Do you] [have the ability to] [teach students to] "…"	Individual (educator)	Competency assessment	BIM**CI** or BLOM
	[Does your organisation] [have] [protocols] [explaining how to] "…"	Organisation (company)	Capability assessment	BIM**CS** and BIMMI
	[Should universities] [teach] [students] [the ability to] "…"	Organisation (institution)	Educational planning	BIM**CI** or BLOM
	[Does the curriculum] [provide for] [students] [to] [learn how to] "…"	Organisation (institution)	Curriculum assessment	
	[Does this] <<team>> [have] [the ability to] "…"	Team (work team)	Competency assessment	∑ BIMCI
		Team (project team)	Competency assessment	
		Team (org team)	Capability assessment	BI**MCS** and BIMMI
	[Does this] [project] [include] [a requirement to] "…"	Project	Requirements assessment	BIMCI
Acquire (The primary action for learning competencies)	[At the end of the] [course], [students] [of] < <course name> > [would] [have learned how to] "*prepare a 3D model for the purpose of linking it to a* <u>*Construction Schedule*</u>"	Individual (student)	Education	BIM**CI** or BLOM
	[You] [will need to] [develop the necessary skills to] "…"	Individual	Development	BIMCI
	[All] <<role group>> s [will receive training in] [how to] "…"	Group (individuals with the same role)	Training	∑ BIMCI
Apply (The primary action for implementing and managing competencies)	[Use] <<software tool>> [to] "*prepare a 3D model for the purpose of linking it to a* <u>*Construction Schedule*</u>"	Individual	Project/org requirement	N/A
	[Work team] <<team code>> [is the responsible party to] "…"	Team	Quality checking	
	…[After completing step] <<step code>> [your] [organisation] [will need to] "…"	Organisation	Project/org requirement	

Legend:

[brackets]	Competency syntax [shown in brackets] is derived from the conceptual BIM Ontology [80].
Italics	Sample competency item is shown in "*italics*" and is to be repeated at each row after the [syntax].
<<chevrons>>	Text in <<chevrons>> indicates variable to be replaced.
BIMCI	BIM competency index (Fig. 2).
∑ BIMCI	Aggregate BIMCI; an arithmetic sum of the competencies of several individuals.
BIMCS	BIM capability stages (Fig. 3).
BIMMI	BIM Maturity Index (Fig. 4).
BLOM	Bloom's taxonomy [49].

10. Concluding remarks

Numerous benefits accrue from identifying, classifying and aggregating generic BIM competencies - devoid of syntax, weight, specialisation, action and delivery method – into a structured inventory. Acting as a *common BIM competency language*, generic competencies can then be customized to *enable or support* the development of BIM-focused *profile and competency management systems* [26,16]; *e-portfolio* and *learning management* systems [79,69,44,56]; continuous *education, training* and *professional development* [83]; and a research-based *BIM-competency certification and accreditation regime* [1,15]. In essence, an integrated approach to competency identification, classification and aggregation will enable the delivery of a comprehensive yet flexible competency-based system for assessment, learning and performance-improvement across both industry and academia:

Across industry, the availability of a structured set of BIM competencies would assist organisations and project partners to:

- Identify BIM goals and objectives through competencies *expressed as abilities*. For example, an organisation can identify the 'ability to deliver BIM-FM services' as a strategic objective to guide its software implementation and recruitment strategy;
- Measure the competency/capability of individuals, organisations and teams using a common reference set. With standardised competency definitions – *expressed as abilities* – individuals, groups, teams, and organisational units can be compared and aligned;
- Define and meet project requirements through standardised competencies *expressed as abilities/requirements*. For example, project activities can be listed and analysed to identify required competencies and to estimate project cost/duration;
- Facilitate organisational and project workflows through competencies – *expressed as activities/tasks*. Task lists can be used to optimise project delivery across an organisation and to facilitate quality checking at different phases of each project's lifecycle;
- Identify pre-qualification criteria through competencies – *expressed as outcomes/deliverables* – within procurement and tender/bid documents; and
- Develop training and continuing professional development (CPD) modules – *expressed as outcomes* – within organisations and industry associations.

Within academia, the availability of a structured set of BIM competencies would assist vocational and tertiary level institutions to:

- Conduct investigations based on a standardised set of BIM competencies – *expressed as abilities*. This reference set could be used to survey industry, establish its competency requirements, and then compare these requirements to current educational deliverables;

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- Identify educational goals related to BIM education[9] through competencies *expressed as learning outcomes*. These goals can inform[10] curricula design and facilitate the development of BIM learning modules;
- Measure the competency of students and lecturers using a common reference set. With standardised competency definitions - *expressed as abilities* – both learner and learning provider can be uniformly assessed against competency topics and sets.

These are the main benefits expected from developing an industry-wide BIM competency inventory. Other benefits are subject to further development of semantic tools which best utilize and extend the use of structured BIM competencies.

11. Future work

This paper has explored individual competencies, the fundamental building blocks of organisational capability. Expanding on previous research, several formative classifications have been introduced and used to develop an integrated definition of *Individual BIM Competency*. This integrated definition acted as a conceptual filter to isolate target competencies which were then classified through a specialized taxonomy and used to populate a seed inventory of generic BIM competencies. A knowledge engine was then introduced to demonstrate how each structured competency item could be used for the complementary purposes of competency acquisition, application and learning.

This research serves as a foundation for future investigations into integrated competency improvement within the DCO industry. Further research is needed to develop a BIM-specific *competence ontology* [22,36] and to match the BIM *competency inventory* with widely adopted definitions and metadata standards [41,39]. Additional efforts are also needed to expand the *competency identification, classification, aggregation* and *multiuse* workflow (Fig. 5) into a framework that supports competency-based learning, assessment and performance improvement. Three main avenues are identified and will be actively pursued to extend this research: first, engaging with industry associations to *gradually* identify, classify and aggregate specialized BIM competencies from across disciplines and specialties; second, developing seed competency-based learning modules which satisfy the BIM educational requirements of sample organisations, industry associations and educational institutions; and third, developing a semantic web-based solution[11] that hosts the *knowledge engine* (Fig. 8) and delivers a set of *integrated* BIM assessment tools, learning objects and workflow modules.

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[9] As noted by Macdonald ([55], page 223), various studies indicate that tertiary education is lagging behind the construction industry in moving towards collaborative, BIM-enabled working practices.

[10] The seed BIM competency inventory has played a role in informing a BIM Education initiative [84] — an industry effort conducted by the Australian Institute of Architects and Consult Australia in 2012.

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PAPER B1

Building Information Modeling: Analyzing Noteworthy Publications of Eight Countries Using a Knowledge Content Taxonomy

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Building Information Modeling: Analyzing Noteworthy Publications of Eight Countries Using a Knowledge Content Taxonomy

Authors: Mohamad Kassem[1], Bilal Succar[2] and Nashwan Dawood[3].

Abstract

Building Information Modeling (BIM) deliverables have the potential to improve the efficiency of design, construction and operation activities. These deliverables and their respective requirements have been widely discussed by industry stakeholders. This is evidenced by the intensity of online communications surrounding BIM topics and the accelerating availability of *noteworthy BIM publications* (NBP)s. NBPs are publically-available industry documents incorporating guidelines, protocols and requirements focusing on BIM deliverables and workflows. These publications are the product of various governmental bodies, industry associations, communities of practice and research institutions, intended to facilitate BIM adoption, and realize BIM's value-adding potential.

A specialized taxonomy is employed to analyze fifty-five noteworthy BIM publications from across eight countries selected for their active BIM scene. The *BIM knowledge content* (BKC) taxonomy includes three *knowledge content clusters* (guides, protocols and mandates) subdivided into eighteen *knowledge content labels* (e.g. report, manual, and contract). Ten of these content labels are used to analyze and compare publications from Australia, Denmark, Finland, the Netherlands, Norway, Singapore, the United Kingdom, and the United States. Content analysis is then performed and provides insight into the availability and distribution of BIM knowledge within noteworthy BIM publications.

This chapter contributes to organizing BIM knowledge as contained within numerous noteworthy BIM publications and – by that - facilitates targeted access to their content. It provides a knowledge repository for construction industry stakeholder's to utilize during BIM implementation and a research base for investigators seeking to identify and address knowledge gaps across the BIM domain.

Introduction

The escalating coverage, connotation and impact of BIM concepts and tools have led to the proliferation of BIM-focused publications. Industry associations, governmental bodies and academic communities across several countries are increasingly developing and releasing a variety of BIM strategy documents, BIM adoption reports, data exchange standards, and model-based collaboration protocols. These noteworthy BIM publications (NBP)s include

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significant knowledge and structured guidance relating to BIM implementation, project delivery and team collaboration. However, the BIM knowledge contained within these documents is rarely analyzed as a whole or labeled accurately as to reflect their true benefit and intended use. Within numerous NBPs (refer to Table 2), many terms – e.g. *BIM protocols*, *BIM guidelines* and *BIM standards* – are either used interchangeably or without qualification. The knowledge content of these NBPs is thus often masked by the documents' surrogates (e.g. titles and headings) and difficult to identify and benefit from. This ambiguity necessitates a *knowledge content identification and organization approach* that (a) shifts attention away from potentially uninformative publication titles and towards their actual knowledge deliverables, and (b) facilitates content analysis, comparison and further development.

Identifying noteworthy BIM publications

Noteworthy BIM publications (NBP)s are publically-available documents developed by various industry and academic entities, aimed at a wide audience, and intended to promote BIM understanding, regulate BIM implementation or mandate BIM requirements. These publications encapsulate extensive BIM-focused knowledge, represent significant domain expertise and are a substantial effort within the BIM domain. To assist in identifying NBPs and informing the selection process, the authors employed explicit ontological structures from the BIM Framework (Succar, 2009) as represented in Figure 1 below:

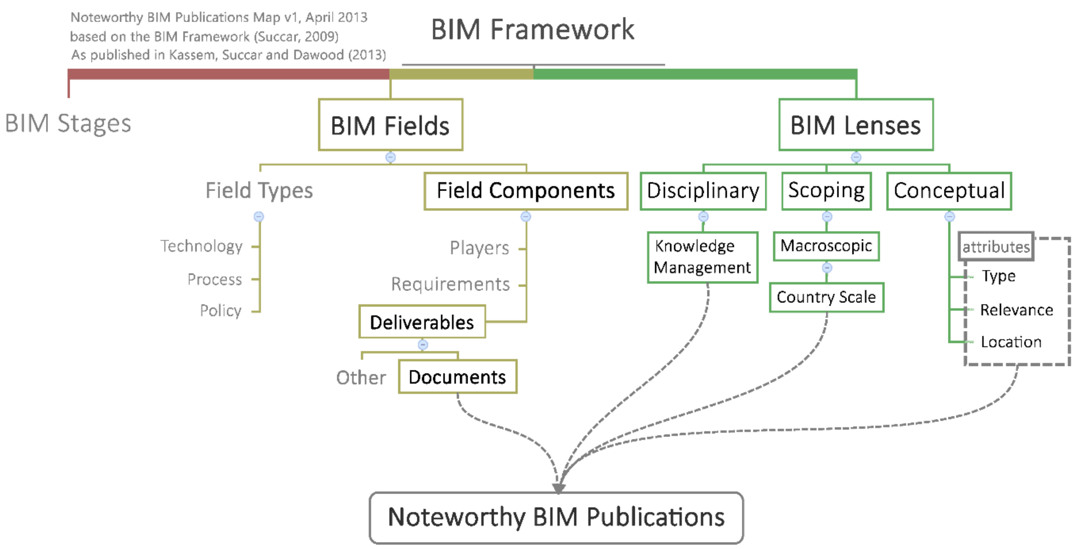

Figure 1. Conceptual derivation of Noteworthy BIM Publications using the BIM Framework

The BIM Framework and its ontological structures are intended to organize domain knowledge and facilitate its understanding. Figure 1 explores how noteworthy BIM publications are derived from the interaction of BIM fields and BIM lenses:

- NBPs are documents (i.e. not websites, blogs or similar);

- NBPs reflect BIM knowledge (i.e. publications focused on BIM skill are excluded);
- NBPs are the deliverables of BIM players (i.e. publications delivered by players from other industries are excluded);
- NBPs cover relevant BIM topics (i.e. publications covering pre-BIM topics are excluded);
- NBPs are macroscopic (i.e. documents aimed at small groups of practitioners or students are excluded); and
- NBPs are selected and organized by country of origin (i.e. NBPs developed across several countries are excluded - e.g. Inpro-EU[4], IDDS[5] or bSI[6]).

Using the above framework-based delimitation, NBPs include numerous types of published documents spanning industry initiatives, peer-reviewed journals, self-published books and other noteworthy publications. However, for the purposes of targeted analysis, this chapter focuses exclusively on publications developed by governmental bodies, industry associations, research institutions and communities of practice.

The next section identifies fifty-five NBPs from across eight countries and provides a succinct summary of their contents.

[4] Open Information Environment for Knowledge-Based Collaborative Processes throughout the Lifecycle of a Building, please refer to http://www.inpro-project.eu/main.asp

[5] Integrated Design and Delivery Solutions, please refer to http://www.cibworld.nl/site/programme/priority_themes/integrated_design_solutions.html

[6] buildingSMART International and their varied noteworthy publications, please refer to http://www.buildingsmart.org/

Identifying NBPs from eight selected countries

Using the ontological structures presented in Figure 1, Table 1 below is a non-exhaustive list of fifty-five noteworthy BIM publications from across eight countries selected for their active BIM scene. The table is organized alphabetically and includes a descriptive summary of each publication's knowledge contents:

Table 1. An indicative summary of noteworthy BIM publications from across eight countries

Code	Document title	Summary Description	Issuer Type	Reference
AU 01	CRC-CI National Guidelines for Digital Modelling + Case Studies (2 documents)	The guidelines document provides an overview of BIM and how it affects current mode of working. It also provides detailed information about model creation/maintenance, modelling procedures and how to initiate large scale BIM projects. The case studies document includes the lessons learned from implementing BIM in six Australian building projects	Research body	CRC-CI, 2009
AU 02	Digital modelling and the built environment, department of Innovation Industry, Science and Research	This report discusses in general terms the benefits and challenges of BIM implementation, and summarizes some of the efforts undertaken both in Australia and overseas	Governmental department	DIISR, 2010
AU 03	Productivity in the buildings network: assessing the impacts of Building Information Models, report to the Built Environment Innovation and Industry Council	This report highlights the economic case for BIM adoption in Australia and suggests a road map for BIM adoption. It includes a discussion about BIM benefits, costs, challenges and opportunities and the results from a survey conducted across the sector	Industry body or association *(based on the work of a consultancy firm)*	BEIIC, 2010
AU 04	NATSPEC National BIM Guide and Project BIM Brief template	The guide provides a summary description of roles and responsibilities, provides guidance on standards and procurement practices and introduces a BIM Management Plan template. The template is also intended for guidance and is intended to assist project participants to decide what information to be included within models at different project stages	Industry body or association	NATSPEC, 2011
AU 05	BuildingSMART Australasia, National Building Information Modelling Initiative	This document discusses benefits and challenges of BIM adoption and surveys international efforts. It's main deliverable is the identification of six interdependent initiatives for government and industry to undertake: procurement, guidelines, education, product libraries, process/data exchange and regulatory frameworks	Industry body or association	buildingSMART, 2012
AU 06	BIM in Practice, an initiative by the	The initiative includes seventeen complementary papers focusing on	Industry body or association	AIA-CA, 2012

Code	Document title	Summary Description	Issuer Type	Reference
	Australian Institute of Architects and Consult Australia	four topics: Legal (4), Industry Outreach (7), Education (3) and BIM Management Plans (3). The papers are exploratory and include summary information intended to inform practitioners and generate discussion within industry		
AU 07	BIM-MEP AUS initiative by the Air Conditioning and Mechanical Contractors' Association of Australia (AMCA)	While focusing on mechanical subcontractors (the associations' members), this industry initiative engages widely with other industry stakeholders and delivers a set of practice guidelines, training material, certified equipment models and software extensions	Industry body or association	AMCA, 2012a
DE 01	BIPS C101: CAD Manual	Outlines guidelines for CAD production and collaboration for the Danish construction industry. This fifth revision replaces "C202: CAD Manual 2005" and "3D CAD Manual 2006, Digital Construction"	Industry body or association	BIPS, 2008
DE 02	BIPS C202: CAD Manual 2008, basic description	Contains guidelines and conceptual descriptions which are applicable across all types of companies and projects	Industry body or association	BIPS, 2008
DE 03	BIPS F103: Object Structure 2008 - June 2008	Specifies uses and data properties pertaining to construction objects (36 objects)at a given level of detail	Industry body or association	BIPS, 2008
DE 04	BIPS F102: Building ICT specifications , instructions - June 2008	Part 1 (see DE 05 for part 2) defines the digital services (BIM deliverables) at different construction project phases and their requirements	Industry body or association	BIPS, 2008
DE 05	BIPS F202: ICT output specification, basic description - June 2008	Part 2 explains technical and practical aspects of digital collaboration between construction project parties	Industry body or association	BIPS, 2008
DE 06	Digital Construction: A Danish government initiative, English introduction, 2010	This strategy document aims to increase information and knowledge sharing between all AEC's actors and improve project efficiency across all phases through the use of BIM tools and workflows	Industry body or association	Det Digitale Byggeri, 2010
FI 01	Senate Properties' Building Information Model Requirements 2007	This document describes general operational procedures to be used in BIM projects with a focus on the design stage. The document is in 9 volumes organized by discipline: 1: General part 2: Modeling of the starting situation 3: Architectural design 4: MEP design 5: Structural design 6: Quality assurance, model merging 7: Quantity take-off 8: Visualization purposes 9: MEP analyses	Government-owned enterprise	Senate, 2007a
FI 02	Senate Properties: BIM Requirements 2007 Volume 1: General part	This is an introductory document to the Finnish BIM guidelines (see FI 03 and FI 04) and includes the general objectives for the generation and	Government-owned enterprise	Senate, 2007b

Code	Document title	Summary Description	Issuer Type	Reference
		utilization of models at different project stages. This document also mandates some BIM uses from October 2007.		
FI 03	Common BIM Requirements COBIM 2012 v1.0”	Updates the “Senate Properties’ Building Information Model Requirements 2007” (FI 01) by adding the following new four series: 10: Energy analysis 11: Management of a BIM project 12: Use of models in facility management 13: Use of models in construction	Government-owned enterprise	Senate, 2012
NL 01	Rgd BIM Standard, Version 1.0.1, July 2012	Guidelines for design and collaboration within BIM environment. The document describes delivery requirements and specifications of BIM extracts (i.e. IFC model, CAD drawings, measurement data, calculations, and quantity take-offs). It also adopts the AIA E202 – 2008 BIM Protocol Exhibit(Levels of Development from the US)	Governmental department	GBA, 2013
NL 02	Public sector demand for BIM	Mandates BIM and the use of IFCon public projects worth more than €10M starting Nov 2011	Governmental department	GBA in Building Smart, 2011a
NL 03	BIM Quickscan: Benchmark of BIM Performance in The Netherlands	An approach for assessing and benchmarking the BIM performance of companies within the Netherlands	Research body	Berlo et al., 2012
NO 01	Statsbygg Building Information Modelling Manual, Version 1.2 (SBM1.2)	Describes BIM requirements with a focus on Industry Foundation Classes (IFC)s”	Governmental department	Statsbygg, 2011
NO 02	Statsbygg goes for BIM	To mandate BIM and the use of IFCs on all public construction projects starting 2010	Governmental department	Statsbygg, 2007
NO 03	Norwegian Home Builders' BIM Manual (ver1)	A manual for Norwegian Home Builders providing practical advice covering BIM processes and utilization	Industry body or association	NHA, 2011
N0 04	The HITOS project – a full scale IFC test	A ‘full-scale IFC test’ documenting experiences gained from a large collaborative BIM project	Industry body or association	Le et al., 2006
NO 05	Construction cost program: Reducing barriers - Report from interview – qualitative (in Norwegian)	A report investigating barriers to BIM collaboration. It discusses efficient construction processes and suggests measures to remove or lower adoption barriers	Government – industry partnership	Byggekostnader, 2010
SG 01	Singapore BIM Guide (ver 1.0)	This document provides guidelines for mono-discipline modeling and multidisciplinary collaboration; describes BIM deliverables of various project members at different project stages and their levels of detail; defines a basic BIM workflow for Design-Bid-Build projects; and offers general guidance on risk allocation, compensation and intellectual	Governmental agency	BCA, 2012

Code	Document title	Summary Description	Issuer Type	Reference
		property rights		
SG 02	All set for the 2015	This document presents Singapore strategy to achieve 80% BIM uptake by 2015 and improve the industry's productivity by up to 25% over the next decade. It also aims to mandate BIM in a phased way: larger projects are required to use BIM for their architectural designs by 2013 and for engineering designs by 2014; smaller projects, both architectural and engineering designs, by 2015	Governmental department	BCA: in BuildSMART, 2011
UK 01	Building Information Model (BIM) Protocol - Standard Protocol for use in projects using Building Information Models, CIC/BIM ProFirst Edition 2013	Guides that identify model-based requirements to be produced project team members: their obligations, liabilities and associated limitations It also includes several intellectual property rights' clauses clarifying permitted uses of models, levels of development and other contractual requirements	Industry body or association	CIC, 2013
UK 02	AEC (UK) BIM Protocol Implementing UK BIM Standards for the Architectural, Engineering and Construction industry - Updated to unify protocols outlined in AEC (UK) BIM Standard for Revit and Bentley Building Version 2.0 September 2012	This document includes guidelines, specific to Revit, Bentley, ArchiCAD and Vectorworks which can be used to inform the creation of BIM elements and facilitate BIM collaboration. It also introduces modeling 'Grades', a system similar to AIA's Levels of Development (LOD)s	Community of Practice	AEC, 2012
UK 03	Soft Landing Strategy	This document aims to align the interests of facility designers and construction companies with those of facility owners and operators. It also introduces a mandate for BIM by 2016 for all Central Government Department projects	Governmental department	Cabinet Office, 2012
UK 04	Government Construction Strategy	This document includes the UK government strategy aimed to challenge current industry business models and practices and replace them with collaborative supply chain models. This document specifies that BIM is a main enabler of this integration and announces the intention of the government to develop 'standards' that enable all members of the supply chain to work collaboratively	Governmental department	Cabinet, 2011
UK 05	BIM Management for value, cost & carbon improvement, report number	This document outlines four BIM maturity levels (0, 1, 2 and 3) intended to categorize technical and collaborative working types and describe processes, tools and	Governmental department	DBIS, 2011

Code	Document title	Summary Description	Issuer Type	Reference
	URN 11/948 - A report for the Government Construction Client	techniques to be used. It also includes workflows that clarify data exchange requirements at specific project milestones It outlines a strategy to increase the BIM adoption over a five year period as part of a wider government strategy aimed to improve construction value and carbon performance and decrease cost		
UK 06	CPIx BIM assessment form	A basic form to assess the BIM capabilities of organizations	Industry body or association	CPC, 2011
UK 07	Building Information Modelling - an introduction for house builders	A manual explaining basic BIM concepts to UK house builders. It includes survey results describing levels of BIM uptake	Industry body or association	NHBC Foundation, 2013
UK 08	Refurbishment resource efficiency case study: Manchester Central Library	A case study demonstrating the benefits of BIM achieved on a $ 61M refurbishment project	Industry body or association	WRAP, 2010
UK 09	National BIM Report 2013	A report providing insight and opinions of UK industry leaders. It includes survey results describing levels of BIM uptake	Private industry	NBS, 2013
UK 10	First Steps to BIM March 2013 Competence A Guide for Specialist Contractors	A report to contractors explaining the BIM fundamentals, business benefits, how to get started with BIM, legal implications, roles and responsibilities	Industry body or association	NSCC, 2013
US 01	GSA BIM guides series	This document includes general guidelines for GSA associates and consultants engaged in 3D and 4D activities. It also contains a section covering data ownership rights	Governmental department	GSA, 2007
US 02	Integrated project delivery: a guide	This document includes guidelines for integrating people, systems, business structures and practices into a project to increase value to the owner, reduce waste, and maximize efficiency through all project phases. It also addresses issues related to multi-party agreements such as risk and reward, liability and dispute resolution	Industry body or association	AIA, 2007
US 03	Contractor's Guide to BIM	This document provides basic guidelines for contractors who intend start using BIM. It also discusses the impact of BIM on responsibilities and liabilities and indicated the areas of risk management for contractors	Industry body or association	AGC, 2006b
US 04	National building information modeling standard - version 1.0 - part 1: overview, principles and methodologies	This document includes a vision for improving the planning, design, construction, operation, and maintenance processes through the use of information models for new and old facilities. The document also defines standard semantics and	Governmental department	NIST, 2007

Code	Document title	Summary Description	Issuer Type	Reference
		ontologies for software to support interoperability. It also presents the Capability Maturity Model (CMM) for the evaluation of the BIM capability of business practices. It also defines a 'BIM Minimum' concept for quantity and quality of BIM information		
US 05	BIM user guides	This document presents guidelines to develop and maintain a BIM standard	Governmental department	USCG, 2005
US 06	BIM guidelines	This document includes requirements for BIM uses/services, submission and design development. It also specifies the ownership of the model including all inventions, ideas, designs, and methods contained within it	Local authority	NYCDDC, 2012
US 07	State of Ohio Building Information Modeling protocol	A document presenting the BIM requirements related to: requests for qualifications, agreements, bidding and contracts, list of deliverables/BIM services, and information exchange It also addresses compensation expectations and level of development of the BIM model at for different project element	Local authority	OHIO DAS, 2010
US 08	Planning Guide for Facility Owners– Version 1.0	This documents present guidelines for the integration of BIM throughout the lifecycle of facilities and in Owners' organizations. It also contains contractual requirements for owners.	Research body	Penn State, 2012
US 09	E203: Building Information Modeling and Data Exhibit	A document defining the levels of development (LoD), the authorized uses of BIM on projects and the responsibility for the defined LOD(s) at each project phase	Industry body or association	AIA, 2012a
US 10	G Document 201: Project Digital Data Protocol Form	A document that includes a contractual form to document the 'digital data protocols' agreed upon by project stakeholders	Industry body or association	AIA, 2012b
US 11	G Document 202: Building Information Modeling Form	A document that includes a contractual to document the 'BIM protocols' agreed upon by project stakeholders	Industry body or association	AIA, 2012c
US 12	Consensus Docs 301 BIM Addendum	This document globally addresses legal and administration issues associated with the use of BIM	Industry body or association	ACGA, 2006
US 13	Building Information Modeling: A Road Map for Implementation To Support MILCON Transformation and Civil Works Projects within the U.S. Army Corps of Engineers	A document presenting the USACE to become a leader in using BIM to improve delivery and management of facilities for the U.S. It also includes strategic goals, plan/milestone to implement BIM, modeling guidelines and workflows, and some general technical requirements	Governmental department	USACE, 2006
US 14	Building Information Modeling (BIM) Roadmap	This document includes workflows that are specific to Bentley platform users working for USACE. It describes the workflows for site analysis, space	Governmental department	USACE, 2011

Code	Document title	Summary Description	Issuer Type	Reference
	Supplement 2 – BIM Implementation Plan for Military Construction Projects, Bentley Platform	programming, architectural design, etc., and presents interoperability requirements and training opportunities		
US 15	BIM Project Execution Planning Guide and Templates – Version 2.0 BIM Project Execution Planning	This document presents guidelines to help the identification of BIM goals and uses and contains process maps and template resources for the the implementation of different BIM uses	Research body	Penn State, 2010
US 16	Construction Operations Building Information Exchange (COBIE): Requirements Definition and Pilot Implementation Standard	This document introduces the 'COBie format specification' as a means for the collection of project data during the project lifecycle phases. It also defines the 'evaluation criteria' for the content of deliverables, the requirements of equipment, product and owner	Governmental department	USACE, 2007
US 17	USACE BIM Minimum Modeling Matrix (M3) V1.0	This document includes a matrix of modeling requirements for BIM deliverables to ensure the relevance of deliverables to all project stages and to the owner and facility manager	Governmental department	USACE, 2012
US 18	The Business value of BIM in North America: Multi-Year Trend Analysis and User Ratings (2007-2012)	This document consists of a report presenting the adoption rates and the uses of BIM in the U.S. and summarizing the results and benefits obtained from five case studies	Private industry	McGraw-Hill Construction, 2012
US 19	NISTIR 7417 General Buildings Information Handover Guide: Principles, Methodology and Case Studies	This document presents strategies and guidelines for the planning, executing and managing of information handovers	Governmental department / Community of practice	NIST and FIATECH, 2007
US 20	IPD Case Studies	This report compares twelve IPD projects - ten of which has used BIM - in terms of contractual and behavioral strategies. It also includes the results of a survey regarding IPD contractual principles and collaborative project delivery methods	Industry body or association / Research body	AIA and University of Minnesota, 2012

Table 1 above introduces numerous noteworthy BIM publications, all intended by their authors to guide BIM implementation and improve workflows and deliverables across the construction lifecycle. Before introducing a specialized taxonomy to classify and analyse these publications, it is important to first explore the importance of well-structured taxonomies in organizing domain knowledge.

Using taxonomies to organize knowledge content

Taxonomies are an efficient and effective way to consolidate knowledge (Reisman, 2005). A well-structured taxonomy allows "the meaningful clustering of experience" (Kwasnik, 1999 - Page 24) and are "a means toward a number of different ends; one of these ends is providing direction and/or guidance to expansion or generalization of knowledge" (Reisman, 1988 – page 216).

Taxonomies originated in biological sciences (Hedden, 2010) and have been used for organizing knowledge in varied domains. For example, taxonomies have been used to facilitate information interoperability and retrieval (Cheng et al., 2010); define semantic conflicts in business databases (Kashyap and Sheth 1996); organize virtual worlds (Milgram and Kishino, 1996); classify diseases (Burgun and Bodenreider, 2001); and categorize human errors in train accidents (Reinach and Viale, 2006). Also within the construction industry, several taxonomies have been developed to organize domain knowledge. For example, Zuppa and Issa (2008) explored a taxonomy documenting the prioritized interests of stakeholders and aligning their interests; El-Diraby, Lima, and Feis (2005) presented a taxonomy for construction management; Sun and Meng (2008) developed taxonomies covering change causes and change effects in construction projects; Garrett and Teizer (2009) presented a taxonomy-enabled educational system for the classifying and analyzing human errors affecting construction safety; and Wang and Dunston (2011) developed a user centric classification of Mixed Reality (MR) approaches within the construction industry.

As a *knowledge organization system* (Hedden, 2010), taxonomies play an important role in clarifying complex topics and facilitating understanding. The next section introduces a specialized taxonomy that assists in understanding the deliverables of noteworthy BIM publications and comparing their knowledge contents.

The BIM knowledge content taxonomy

There are numerous noteworthy BIM publications covering a large number of overlapping BIM topics. The knowledge contained within these publications may be masked by the document's chosen title and inconsistent use of terminology across different documents. To facilitate access to the knowledge contents across noteworthy BIM publications and enable their comparison and analysis, this chapter introduces the BIM Knowledge Content (BKC) taxonomy. The BKC taxonomy is derived from explicit ontological structures of the BIM Framework (Succar, 2009) (Succar, 2013) as described in Figure 2 below:

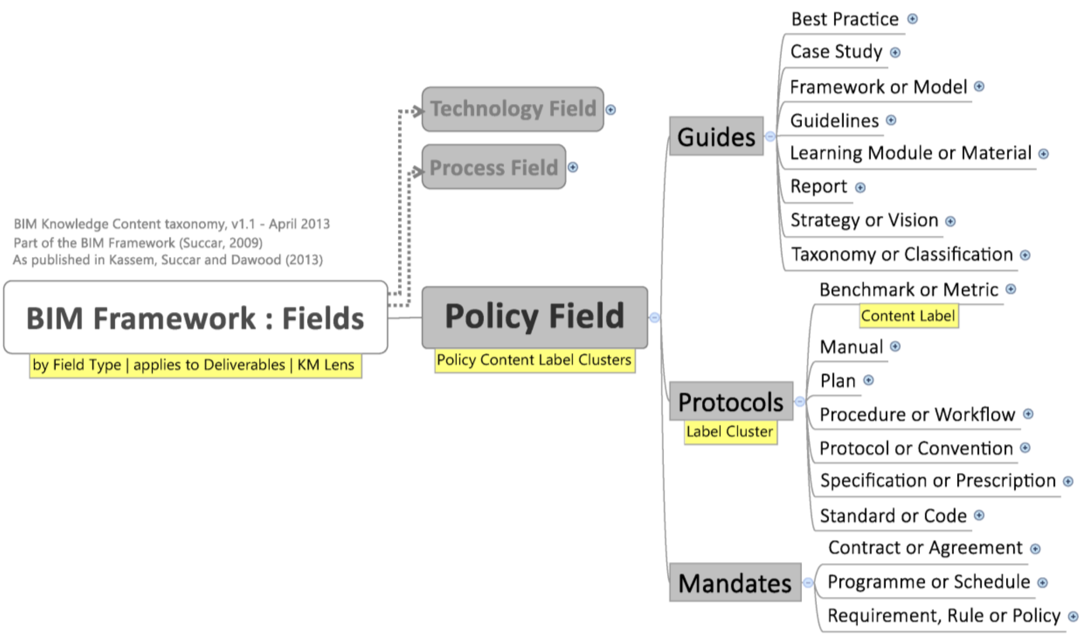

Figure 2. The BIM Knowledge Content taxonomy – Mind Map

As described in Figure 2 above, the BIM Knowledge Content taxonomy includes three *knowledge content clusters* – Guides, Protocols and Mandates:

- **Guides**: documents which are *descriptive* and *optional*. Guides clarify goals, report on surveys/accomplishments or simplify complex topics. Guides do not provide detailed steps to follow to attain a goal or complete an activity.
- **Protocols**: documents which are *prescriptive* and *optional*. Protocols provide detailed steps or conditions to reach a goal or deliver a measureable outcome. While documents within this cluster are prescriptive, they are optional to follow unless dictated within a Mandate (see next cluster).
- **Mandates**: documents which are *prescriptive* and *dictated* by an authority. Mandates identify *what* should be delivered and – in some cases – *how, when* and *by whom* it should be delivered.

Each of the knowledge content clusters includes a number of *knowledge content labels* to identify and delimit specific knowledge types. Table 1 below lists the eighteen labels and provides a summary of their BIM-specific definitions:

Table 2. BIM Knowledge Content taxonomy – 18 content labels in 3 content clusters

Content CLUSTER	Label CODE	Content LABEL	Label DEFINITION - BIM specific
Guides	G1	Best Practice	Operational methods arising from experience; promoted as advantageous; and replicable by other individuals, organizations and teams. This *label* applies to publications which list unambiguous and detailed recommendations, and which if applied as recommended, generate similar advantageous outcomes

	G2	Case Study	Summary and analysis (descriptive or explanatory) of projects and organizational efforts. This *label* applies to both research and industry publications which share lessons learned *by others,* and cover BIM deliverables, workflows, requirements, challenges and opportunities
	G3	Framework or Model	Theoretical structures explaining or simplifying complex aspects of the BIM domain by identifying meaningful concepts and their relationships
	G4	Guideline	Compilation of several BIM content types with the aim of providing guidance to individuals, teams or organizations. Guides typically provide insight into a complex topic (e.g. BIM Implementation Guide or Facility Handover Guide). Guides typically focus on knowledge-intensive topics, while Manuals (a complementary label) focus on skill-intensive ones. Due to the generic nature of this *label*, it should <u>not be applied in isolation</u> but in conjunction with other labels
	G5	Learning Module or Material	All types of analogue and digital media (e.g. printed manual or online videos) which deliver conceptual or practical insight intended/suitable for education, training or professional development within industry or academia
	G6	Report	Compilation or summary of results arising from an assessment, calculation or review process (e.g. BIM capability report or profitability statement)
	G7	Strategy or Vision	Articulation of vision, mission and long-term goals. This *label* applies to publications which identify a long-term strategy (and possibly middle-term goals/milestones) but without identifying the resources required and detailed steps needed to fulfill the strategy
	G8	Taxonomy or Classification	Classification covering roles, types, levels, elements and other structured concepts. This *label* applies to publications which introduce classifications of five or more items within a structured list; and which have a clear use in assessment, learning or implementation (e.g. construction elements, BIM roles, data exchange types or levels of detail)
Protocols	P1	Metric or Benchmark	Tools and criteria suitable for establishing levels of performance of systems, projects, individuals, teams, organizations and other organizational units[7]. This *label* applies to publications which include tools or explicit metrics/indicators for establishing usability, profitability, productivity, competency, capability or similar
	P2	Manual	A structured document which is intended to clarify the steps needed to perform a measureable activity or deliver a measureable outcome (e.g. BIM Training Manual). Manuals typically focus on skill-intensive topics, while Guides (a complementary label) typically focus on skill-intensive ones. Due to the generic nature of this *label*, it should <u>not be applied in isolation</u> but in conjunction with other labels
	P3	Plan	A document describing activities to be performed, resources to be used and milestones to be reached within a defined timeframe. This *label* applies to publications describing – in adequate detail - how a specific strategy can be fulfilled or a pre-defined goal can be reached (e.g. a BIM Implementation Plan detailing how to fulfill a BIM Capability Strategy)
	P4	Procedure or workflow	Structured information covering successive steps needed to fulfill an operational, rather than strategic, requirement. A documented Procedure includes the small steps needed to deliver, if executed by a competent individual, a pre-defined and desired outcome. A Workflow identifies major successive activities to be performed and

[7] There are 12 organizational units, each with their own unique metrics (refer to Building Information Modelling Maturity Matrix (Succar, 2010).

			decision gates to pass-through towards reaching a delivery milestone or fulfilling a project/organizational objective
	P5	Protocol or Convention	Agreed or customary method of product/service development or delivery which are not *by themselves* contractually binding (e.g. keeping minutes of meetings, how to name files and frequency of exchanging models)
	P6	Specification or Prescription	A set of criteria used to define or judge the quality of products (e.g. object dimensions or data richness) and services (e.g. timeliness). Specifications may or may not be a Standard (a separate label). COBie is an example of BIM-related specifications which may become a service/delivery standard over time
	P7	Standard or Code	Detailed set of product/service descriptions (prescriptive or performance-based) acting as a reference to be measured against. This label typically denotes a set of specifications (a separate label) which are authoritative and test-proven (e.g. barrier-free or accessibility standards)
Mandates	M1	Contract or Agreement	Legally-binding document and its subparts – including contractual additions, amendments and disclaimers. This *label* applies to contracts and clauses, not to publications describing or promoting them (e.g. the label applies to AIA Documents E203, G201 and G202 but not to the AIA IPD guide)
	M2	Program or Schedule	A document associating one or more classification to time and/or location. For example, a BIM competency improvement program is a document linking BIM competencies, BIM roles (and possibly other classifications) to a timeline or target dates
	M3	Requirement, Rule or Policy	Expectation or qualification mandated by clients, regulatory authorities or similar parties. This *label* applies to publications with explicit identification of requirements to be met (e.g. organizational capability or previous experience) or products/services to be delivered (e.g. a tender/bid document)

The BKC taxonomy explored in Table 2 includes three content clusters and eighteen content labels. These clusters and labels facilitate the examination of noteworthy BIM publications by "[shifting] the focus of perusal and interaction away from potentially uninformative document surrogates (such as titles, sentence fragments and URLs) to actual document content, and uses this content to drive the information seeking process" (White, Jose and Ruthven, 2005 - page 1). Also, by defining a *common vocabulary* to identify knowledge contents (Holsapple and Joshi, 1999), the BKC taxonomy is able to organize a large extent of disjointed domain knowledge into a structure that is useful, accurate and trustworthy (Forze and Di Nuzzo, 1998).

Analysis of BIM publications using knowledge content taxonomy

The BIM knowledge content taxonomy includes eighteen content labels intended to analyze the BIM knowledge contained within publications and other knowledge sources. Ten of these labels have been chosen from across the three content clusters and applied to the fifty-five noteworthy BIM publications from eight different countries (Table 1). The distribution of these content labels is explored in Table 3 below:

Table 3. An exploration of 55 NBPs from eight countries using the BKC taxonomy

		Guides				Protocols				Mandates	
		Case Study	Guideline	Report	Strategy or…	Metric or…	Manual	Procedures or…	Specifications…	Contract or…	Requirement…
		G2	G4	G8	G9	P1	P2	P4	P6	M1	M3
Australia	AU 01	●	●				●				
	AU 02			●							
	AU 03			●							
	AU 04		●					●			
	AU 05			●	●						
	AU 06		●								
	AU 06		●				●	●	●		
Denmark	DE 01		●								
	DE 02		●								
	DE 03					●			●		
	DE 04										●
	DE 05						●				
	DE 06				●						
Finland	FI 01		●			●					●
	FI 02				●						
	FI 03		●			●					●
Norway	NO 01		●								●
	NO 02				●						
	NO 03						●				
	NO 04	●									
	NO 05			●							
Singapore	SG 01		●			●		●		●	
	SG 02				●						●
The Netherlands	NL 01		●						●		●
	NL 02				●						
	NL 03					●					
United Kingdom	UK 01		●			●				●	
	UK 02		●			●					
	UK 03				●						●
	UK 04				●						
	UK 05			●	●	●		●			
	UK 06					●					
	UK 07						●				
	UK 08	●									
	UK 09			●							
	UK 10			●							
United States	US 01		●							●	
	US 02		●							●	
	US 03		●							●	
	US 04		●		●	●					
	US 05		●								
	US 06					●				●	●
	US 07					●				●	●
	US 08		●								●

	Guides				Protocols				Mandates	
	Case Study	Guideline	Report	Strategy or…	Metric or…	Manual	Procedures or…	Specifications…	Contract or…	Requirement…
	G2	G4	G8	G9	P1	P2	P4	P6	M1	M3
US 09					●				●	
US 10									●	
US 11									●	
US 12									●	
US 13		●		●						●
US 14						●	●			
US 15		●					●			
US 16								●		●
US 17					●					
US 18	●		●							
US 19	●	●		●						
US 20	●		●							

The fifty-five noteworthy BIM publications analyzed in Table 3 above include a substantial sum of specialized BIM knowledge. However, the coverage and distribution of this BIM knowledge varies significantly across the eight countries. Using Tables 1 and 3 as a guide, the paragraphs below provides a succinct analysis of the BIM knowledge content available to stakeholders within each country:

Australia

As indicated by surveys and workshops conducted within the last few years, BIM tools and workflows are increasingly being adopted across the Australian construction industry (BEIIC, 2010) (buildingSMART, 2012). These surveys however do not clarify BIM adoption rates across all disciplines or the quality/consistency of BIM deliverables.

Using the Noteworthy BIM Publications as an indicator, NBPs emanating from Australia show an abundance of reports discussing the benefits, risks and challenges of BIM implementation. While many of these publications overlap in arguing the case for model-based workflows and suggesting roadmaps for industry-wide adoption, only a few publications provide implementation steps or detailed protocols for industry practitioners to follow. These represent a handful of seed BIM specifications and procedures (AMCA, 2012) (NATSPEC, 2011) (ANZRS, 2011) which have been developed and highlight significant knowledge gaps that still need to be addressed. For example, Australia's NBPs do not include a BIM-ready classification system - similar to UniClass2 (UK) and OmniClass Table 21 (US) – which is key for uniform exchanges of model objects, cost information and other metadata.

Table 3 also identifies a lack in *mandates* – typically developed by governmental units or large client bodies – that define BIM requirements and thus encourage BIM adoption. With the absence of such mandates, industry associations and advocacy groups – not governmental bodies - are still the main players who are "actively driving the development of standards and protocols for the generation and exchange of building information" (CIBER, 2012, page 19).

In summary, the unequal distribution of NBPs across the three *content clusters* highlights a fundamental challenge facing industry stakeholders in Australia: overlapping guides, insufficient protocols and a complete lack of governmental mandates.

Denmark

Denmark is one of the first countries to actively develop BIM guidelines and protocols. Their earliest version of their BIM guidelines called BIPS (BIPS, 2008) was released in 2007. Also, BIM deliverables were partially mandated on public sector projects worth more than DKK 40M ($7M) and architects, engineers and contractors working on government projects were required to use a number of new digital routines, approaches and tools (Kubba, 2012). Additional guidelines for digital collaboration between stakeholders were issued in 2008 (refer to DE 05 in Table 1). A simple analysis of the time each guide and mandate was issued indicates a steady process of developing guidelines and mandating BIM on projects of increasingly smaller value over time. Indeed, in 2010, BIM was mandated on all projects worth more than DKK 20 M ($ 3.5 M), a 50% drop from the previous threshold of DKK 40M ($7M) (refer to DE 06 in Table 1). Moreover, this already low threshold was further decreased following the decision of the Danish Government to mandate BIM on all central government projects worth more than DKK 5M ($ 870K) (Building SMART, 2011b). Also, the Danish Digital Construction initiative (refer to DE 06 in Table 1) specified that stakeholders working on public construction projects should use the following four means: (1) electronic tendering submission system based on a specified bill of quantities and a portal for submitting tenders; (2) a project web environment for participants to share project data and exchange documents, drawings and specifications; (3) 3D models interchangeable in IFC format to be used across all project lifecycle phases; and (4) electronic hand-over of data from the construction project as relevant for facility operation (Det Digitale Byggeri, 2010).

It is important to observe strong BIM leadership in Denmark is stemming from the public sector (i.e. from the Palaces and Properties Agency, Danish University, Property Agency and Defence Construction Service). Also, as early as 2006, 50% of architects and 40% of engineers in Denmark were using BIM in some parts of their projects (Kubka, 2012).

The distribution of NBPs emanating from Denmark provides a clear picture of the country's BIM landscape. NBPs are well-distributed among the three clusters (Guides, Protocols and Mandates). However, the number of legal documents and case studies in Denmark is surprisingly low despite the aggressive digital procurement routes adopted in Denmark since early 2007. Also Table 3 indicates a lack in both BIM workflows to clarify project processes and assessment tools to manage BIM competencies.

Finland

Finland exhibits a considerable commitment to BIM adoption by both the public and private sectors. As evidenced by NBPs listed in Table 1 both public and private entities have been collaboratively involved in conducting BIM pilot projects and developing BIM guidelines since the early 2000s. Also, according to Kiviniemi (2007), BIM surveys conducted in Finland report high BIM adoption rates by architects (93%) and engineers (60%). The Finnish BIM guidelines, based on an R&D project called 'ProIT', were also widely supported by industry (Kubba, 2012). Finally, Senate Properties, the government owned enterprise responsible for managing the property assets of the Finnish state, started requiring BIM/IFC on their projects in October 2007 (Senate, 2007b).

The distribution of NBPs emanating from Finland (Table 3) indicates several gaps within the protocols and mandates clusters. Multi-volume, discipline-specific BIM guidelines (refer to FE 01 in Table 1) provide an introduction into the fundamentals of product modeling yet do not introduce any data exchange specifications. Also, despite that clients can request the use of BIM for design validation, energy simulation, structural analysis and other analyses, there are no publically-available contractual guidelines that address liability issues, compensation matters and intellectual property rights. Furthermore, there are still no available metrics to assess the BIM capabilities of organizations or documented workflows to assist in streamlining BIM project delivery.

Norway

The Norwegian BIM guidelines called "Statsbygg Building Information modeling Manual – version 1.2" were developed in coordination with the American National Institute of Building Science's NBIMS (National BIM Standard) (Wong et al., 2009). Statsbygg is the Norwegian government's key advisor in construction and its building commissioner, property manager and property developer. Statsbygg conducted several pilot projects using Industry Foundation Classes (IFC)s starting in the early 2000s (refer to NO 04 in Table 1). Following these, BIM guidelines were developed (NO 01) and BIM was mandated on all public sector projects starting from 2010 (NO 02). However, although the demand for BIM is promoted and mandated by the public sector, industry associations have also been active in developing their own BIM manuals. For example, the association of Norwegian Home Builders developed their own BIM manual (refer to NO 03 in Table 1) to provide practical advice associated with BIM processes, modeling and utilization (NHA, 2011).

NBPs emanating from Norway include a higher concentration of *guides* as opposed to *protocols* and *mandates* (refer to Table 3). Among the gaps detected are the absence of metrics or benchmark to facilitate performance assessment/improvement and no defined BIM workflows to assist in structuring model-based exchanges. Although BIM has been mandated on all projects starting 2010, there are still no contractual documents that address the specific legal and intellectual property issues arising from BIM implementation.

Singapore

Public sector organizations in Singapore such as Building and Construction Authority (BCA) - in collaboration with private entities such as the Construction and Real Estate Network (CORENET) - are taking the lead in adopting and mandating BIM adoption. The BCA, an agency under the Ministry of National Development, delivers many programs to raise awareness including workshops, roadshows and promoting success stories (e.g. ArtScience Museum, Housing projects by the Housing and Development Board) (BuildingSMART, 2011b) . The agency also assists industry stakeholders to build capability and capacity through a 'BCA Academy' that delivers BIM training programs to equip public sector consultants and contractors (Building SMART, 2011b) and a 'BIM Fund' that partially covers the costs for BIM adoption by organizations (Building SMART, 2011b). Finally, the BCA has mandated a phased BIM implementation program: larger projects are required to use BIM for their architectural designs by 2013 and for engineering designs by 2014; and smaller projects, both architectural and engineering designs by 2015 (refer to SG 02 in Table 1).

It is also important to note that Singapore pioneered a BIM-specific 'e-Submission System' (eSS) that supports IFC and allows AEC organizations to submit their project documents over the internet (CORENET eSS, 2009). Singapore also has ambitious goals to increase overall BIM adoption rates to 80% by 2015 - as stated in their BIM roadmap (refer to SG 02 in Table 1) - up from 10% in 2008 and 25% in 2011 (buildingSMART, 2011b).

Analysis of Singaporean's NBPs (refer to Table 3) indicates a holistic and top-down approach to BIM adoption. While labels from all the three clusters exist within the analyzed NBPs, BIM assessment benchmarks for BIM capabilities and competencies are still lacking. This is somewhat unexpected given the on-going BIM training and certification program driven by BCA. Also, with the exception of BIM workflows adopted from Penn State's Computer Integrated Construction (CIC) Research Group (Penn State, 2010), Singapore's BIM guide (refer to SG 01 in Table 1) still lacks well-documented workflows to guide BIM project delivery.

The Netherlands

The Dutch BIM guidelines called "Rgd BIM Standard" (refer to NL01 in Table 1) and the Dutch BIM Strategy (NL 02) has been first issued in 2012. BIM deliverables - through the IFC format – have been mandated on all projects worth more than €10M starting from November 2012. According to Dr. Alex Vermeulen, director of Rgd, A&A, the expectations behind the guidelines and strategy is that models of existing buildings should be delivered using both proprietary and non-proprietary formats (i.e. IFC) and kept live throughout the building's lifecycle (Building SMART, 2011b). The Dutch guidelines also identifies the legal responsibility covering BIM exchanges and adopts levels of development (LOD)s from the "AIA E202 – 2008 BIM Protocol Exhibit" as a basic measure to identify model-based deliverables. Also, the Dutch guidelines employ 'BIM Quick Scan' (refer to NL 03 in Table 1), a benchmarking tool developed by TNO, for assessing the BIM performance of organizations.

Analysis of Dutch NBPs reveals a balanced distribution across the three content clusters despite the relatively recent release of these publications. This indicates that Dutch BIM policy makers may have benefited from the experiences of other countries. Finally, and similar to other reviewed countries, there are still no documented BIM workflows or procedures to reflect the specific attributes of the Dutch construction industry.

The United Kingdom

The United Kingdom has been active in developing strategies and BIM policies for improving the performance of its construction industry. In May 2011, the UK Government published its "Government Construction Strategy (GSC)" (refer to UK 04 in Table 1) which emphasized the need to develop standards for enabling all members of the supply chain to work collaboratively through BIM. The strategy also announced that the "Government will require fully collaborative 3D BIM (with all project and asset information, documentation and data being electronic) as a minimum by 2016" (refer to UK 03 in Table 1).

A "BIM Task Group" bringing together the expertise from industry, government, public sector, institutes and academia, was formed and tasked to deliver the Government strategy. The first version of the UK BIM guidelines was then developed and released in 2013 (UK 01) and identified three major milestones (called maturity levels) for industry to aim for: Level 1 (2d/3D CAD file based collaboration), Level 2 (BIM file based collaboration), and Level 3 (fully open and integrated web service environment). The Task Group then went on to mandate deliverables to be at Level 2 by 2016. Compared to Singapore which mandated Level 3 UK-equivalent by 2015, the UK strategy seems much less ambitious. However, this phased approach to BIM implementation -recommended by a Strategy Paper to the Government Construction Client Group (refer to UK 05 in Table 1) – actually reflects how most UK firms are still at Level 1.

To support the implementation of BIM Level 2, several NBPs have been lately released. These include 'BS 1192' by the British Standards Institution (BSI) which establishes a methodology for managing the production, distribution and quality of construction information. The British BIM guidelines also contains some contractual guidance covering intellectual property rights and the incorporation of BIM protocols into all direct contracts between the employer and the project team members.

In addition to the publications sponsored/released by the UK government and BSI, industry associations are also playing a significant role in releasing NBPs. For example, the Royal Institute of British Architects (RIBA) has updated their popular RIBA 'Outline Plan of Work' to include a 'BIM Overlay' (RIBA, 2012) reflecting the changes BIM introduces to different project phases.

NBPs emanating from the UK incorporate nearly all knowledge content labels. However, despite the recency of most of these publications, there are many similar deliverables and much duplicated effort (refer to Table 3). Organizational assessment metrics (refer to UK 06 in Table 1) are still elementary and not based on grounded research. Also, with the exception of workflows showing 'data-drop stages for COBie'[8] there are still limited documented workflows which clarify BIM implementation or collaboration procedures.

United States

The United States is the most prolific producer of noteworthy BIM publications. This is primarily driven by the numerous industry bodies (e.g. AGC, AIA and GSA), governmental agencies (e.g. NIBS, USACE, USCG, and NIST) and local authorities (e.g. NYCDDC and OHIO DAS) which have been actively developing their BIM guides and mandating BIM use since 2007. According to McGraw Hill Construction (2012), BIM adoption rates among contractors, architects and engineers in 2012 are at 74%, 70% and 67% respectively.

Many US noteworthy BIM publications, especially those developed by governmental agencies, are addressed to contractors or intended to facilitate the delivery/handover of facilities to operators upon construction completion. NBPs with a more holistic view are those developed by the NIBS (refer to US 04 and US 20 in Table 1) which continue to act as reference documents for other institutions and bodies. For example, the "National Building Information Modeling Standard" (refer to US 04 in Table 1) covers most topics related to BIM implementation and collaboration and includes a BIM capability maturity model for performance assessment.

NBPs emanating from the US are well distributed across all three content clusters - guides, protocols and mandates. Some of these NBPs are very similar and represent a partial duplication of effort among industry bodies (e.g. between US 01, US 02 and US 03 in Table 3) and among local authorities (e.g. between US 06 and US 07 in Table 3). Another significant characteristic of US NBPs is the availability of workflows and procedures covering all project lifecycle phases (e.g. US 14 and US 15). Also, US NBPs include an abundance of mandates (e.g. contractual templates and procurement requirements) developed by governmental agencies and large client bodies. These mandates represent a clear indication of the leading roles these bodies play in shaping and driving industry-wide BIM adoption.

Comparison of BIM knowledge content across countries

The BIM knowledge content (BKC) taxonomy is used to analyze noteworthy BIM publication (NBP)s across eight countries selected for their active BIM scene. This taxonomic approach allows comparisons to be drawn between different publications and between different

[8] For an example, please refer to http://www.bimtaskgroup.org/wp-content/uploads/2012/03/COBie-data-drops-29.03.12.pdf, last visited April 29, 2013

countries. As a tiered classification, the three label clusters with their distinct properties (*guides* are descriptive and optional; *protocols* are prescriptive and optional; and *mandates* are prescriptive and dictated) - provide an insight into the BIM scene of each country. Some countries have a balanced distribution between clusters (e.g. Singapore and the US) while others have an unbalanced distribution and even lack knowledge contents within a specific cluster (e.g. Australia).

Figures 3, 4 and 5 below provide a visual analysis of the number, percentage and distribution of content labels across the noteworthy BIM publications of the eight selected countries:

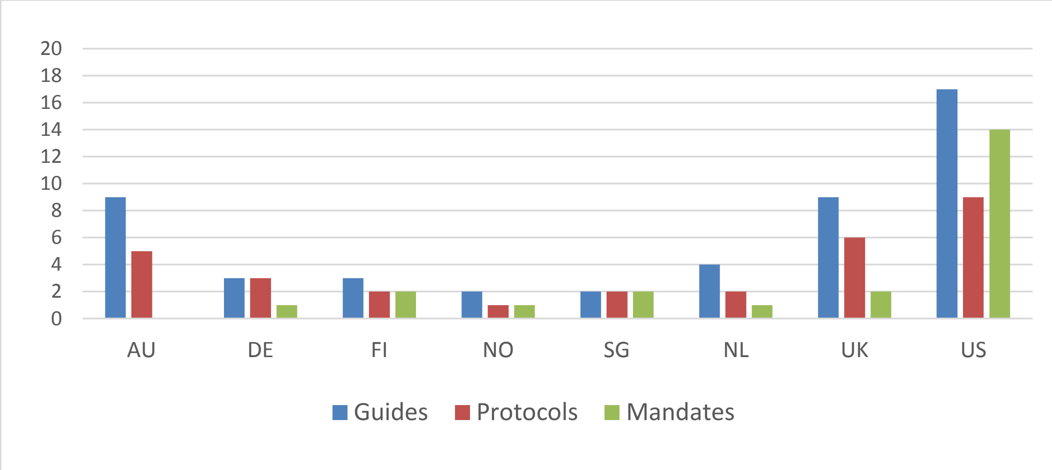

Figure 3. Distribution of guides, protocols and mandates within countries

Figure 3 above highlights the large number of publications emanating from the US and the UK by collating the number of BIM knowledge content labels.

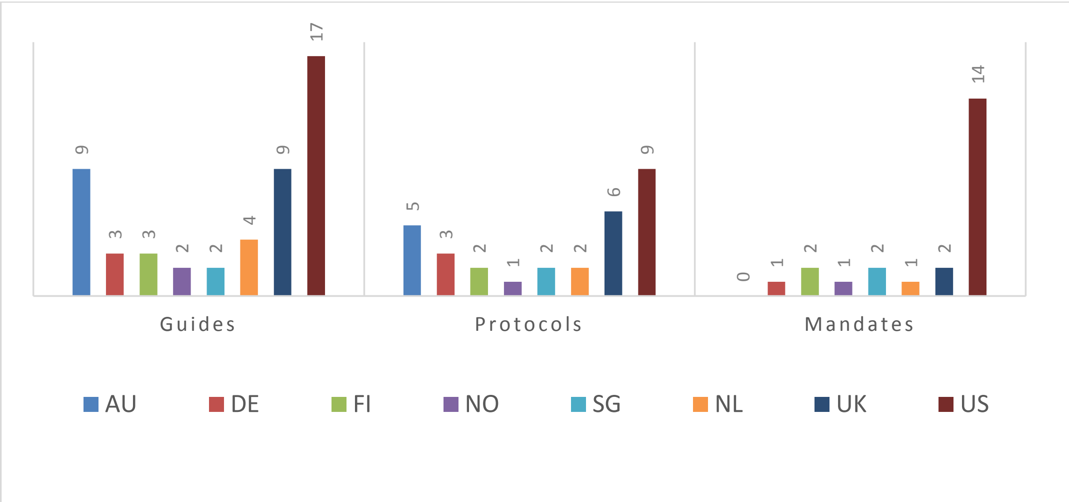

Figure 4. Comparison between the number of guides, protocols and mandates across countries

Figure 4 above highlights the leading position the US occupies with respect to generating the largest number of NBPs across all three clusters. It also specifically highlights the large number of mandates emanating from the US as compared to all other surveyed countries.

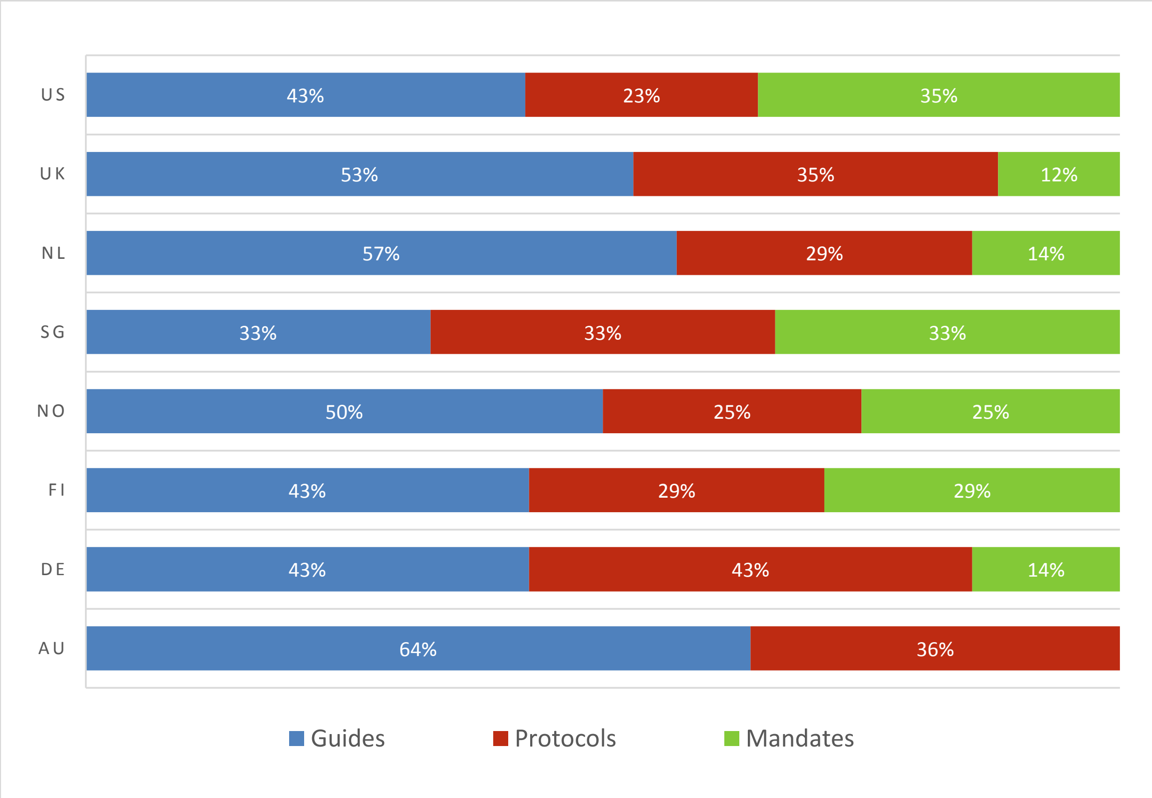

Figure 5. Relative distribution and comparison of guides, protocols and mandates across and within countries

Figure 5 above highlights the relative distribution of NBPs across the three labels. It also highlights the difference between a balanced distributions (e.g. that of Singapore) and an unbalanced distribution across clusters (e.g. that of Australia).

Concluding notes

Noteworthy BIM publications encapsulate a significant volume of domain knowledge. By organizing the knowledge content across these publications, industry-wide comparative analysis and knowledge gap identification can be achieved.

This book chapter introduced a BIM knowledge content taxonomy derived from a published BIM Framework (Succar, 2009) (Succar, 2013). The BIM content taxonomy consists of a hierarchical cluster of eighteen content labels grouped under three content clusters with specific taxonomic properties. The BIM content taxonomy can be utilized in two main ways: organize BIM domain knowledge, and enable targeted access to specific content within numerous publications.

Organizing BIM domain knowledge allows policy makers and field researchers to identify gaps in their country's BIM policies and to highlight areas which require further research and development. Policy makers can also adopt or adapt compatible BIM content types from other countries and thus reduce duplication of efforts. Also, the BKC taxonomy can be used to facilitate access to knowledge spread across a large number of publications. Analysis and comparison can be continuously extended to include new publications or to generate more granular labels which pinpoint specific knowledge types.

In this chapter, ten content labels from the BIM knowledge content taxonomy were used to classify fifty-five noteworthy BIM publications from eight countries selected for their active BIM scene. Analysis of content availability and their distribution provided a structured insight into much published BIM knowledge. Future studies will aim to expand the BIM content taxonomy by considering more granular labels. An online database-driven, web-based prototype will also be developed to further organize domain knowledge and allow extended research findings to be efficiently maintained, managed, and accessed (Zuppa and Issa, 2008). Noteworthy BIM publications from additional countries will also be analyzed and compared to provide a wider and more structured understanding of available BIM knowledge content, decrease effort duplication across the wider industry and facilitate BIM adoption.

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PAPER B2

Building information modelling framework: A research and delivery foundation for industry stakeholders

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A PROPOSED APPROACH TO COMPARING THE BIM MATURITY OF COUNTRIES

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ABSTRACT

BIM concepts and tools have now proliferated across the construction industry. This is evidenced by the comparative results of BIM adoption rates reported through a number of industry surveys. However these surveys typically cover a small number of industry stakeholders; are intended to establish adoption rates by organizations rather than markets; and are unsupported by theoretical frameworks to guide data collection and analysis. Based on a published theoretical framework, this paper proposes three metrics to augment survey data and help establish the overall BIM maturity of countries. These metrics apply to noteworthy BIM publications (NBP)s and assess their BIM knowledge content (BKC). NBPs are publically-available industry *documents* intended to facilitate BIM adoption; while BKCs are specialized *labels* (e.g. report, manual, and contract) used to describe NBP contents. The three metrics – *NBP availability*, *NBP content distribution,* and *NBP relevance* - are applied in assessing the knowledge deliverables of three countries – United States, United Kingdom and Australia - chosen for their similar construction culture and active BIM scene. The paper then discusses how these complementary metrics can inform policy development and identify market-wide knowledge gaps.

Keywords: Building Information Modeling (BIM), Country-scale BIM maturity, Noteworthy BIM Publications, BIM Knowledge Content taxonomy.

1. INTRODUCTION

This paper adopts a wide-angle approach to BIM maturity as applicable to countries rather than organizations. Assessing maturity at this large scale is conceptually supported by a published framework used as a basis for proposing new qualitative metrics to complement quantitative surveys conducted in three countries. For the purposes of simplification and targeted exploration, we propose three - out of many possible - qualitative metrics; focus on three countries with similar construction cultures; and steer away from differentiating between BIM readiness, adoption, diffusion, infusion and maturity. These self-imposed limitations are intended to facilitate this exploration of country-wide BIM maturity and will be removed in future more detailed studies.

1.1 COUNTRY-SCALE BIM MATURITY

BIM maturity refers to the quality, repeatability and degrees of excellence in delivering a BIM-enabled service or product (Succar, 2010). There are an increasing number of BIM-specific maturity frameworks (Giel and Issa, 2012) (Chen, Dib and Cox, 2012) (Mom and Hsieh, 2012). Many of these frameworks are intended to measure the performance of organizations and teams but are not applicable across all *organizational scales* (Succar, 2010). For example, there are several maturity models available for assessing *organizational BIM capability/maturity* (TNO, 2011) (NIST, 2007) (BIMe, 2013) (Succar, 2010), *BIM project performance* (IU, 2009) (Suermann, Issa and McCuen, 2008) (BIMScore, 2013) (BIMe, 2013), and *individual BIM competency* (Succar 2013) (BIMe, 2013). However, metrics suitable for assessing macro organizational scales – e.g. market, industry or country scales - are nearly absent in the construction industry.

Country-scale maturity studies are however available across a number of disciplines, yet are nearly absent in the construction industry, in general, and the BIM domain in particular. For example, there are both qualitative and quantitative metrics for assessing e-Government maturity, and have been applied in measuring the online presence of governments across 22 different countries (Accenture Consulting, 2004). Country-scale e-Commerce maturity models are also available and identify three distinct stages - experimentation, ad-hoc implementation and integration – for establishing maturity (iKPMG, 1997 and Zandi, 2013).

With the absence of specialized maturity metrics, analyzing quantitative survey data collected by prominent industry associations (e.g. McGraw-Hill Construction, 2012; NBS, 2013 and BuildingSMART, 2012) has been the only readily available option. This paper introduces additional metrics to augment survey data in establishing country-scale maturity.

1.2 Underlying conceptual framework

Assessing and comparing country-scale BIM maturity is conceptually based on the theoretical framework developed by Succar (2009, 2010). The framework's components – those applicable to this paper - are briefly described below:

- **Organizational Scales:** the framework identifies three scales: **Macro** - markets and industries; **Meso** - projects and their teams; **Micro** - organizations, units, their teams and members. Each of these scales is further divided into more granular organizational scales. There is a total of 12 organizational scales with the *organizational member* as the smallest scale, to the *international market* as the largest scale. This paper applies one of the macro scales - *Defined Markets* - to focus on country-level maturity.
- **BIM Maturity:** the framework identifies five distinct levels of maturity (Initial, Defined, Managed, Integrated and Optimized) that can be applied at all organizational scales. Levels represent the progression from lower to higher levels of maturity and indicate (i) improved control resulting from fewer variations between performance targets and actual results, (ii) enhanced predictability and forecasting of reaching cost, time and performance objectives, and (iii) greater effectiveness in reaching defined goals and setting new more ambitious ones (Lockamy III & McCormack, 2004) (McCormack, Ladeira, & Oliveira, 2008). *This paper adopts the BIM maturity definition as introduced in the framework.*
- **BIM Fields** and **BIM Lenses** and their delimitations: these are discussed in some detail in section 1.3.

1.3 Noteworthy BIM Publications

Noteworthy BIM publications (NBP)s are publically-available documents developed by various industry and academic entities; aimed at a wide audience; and intended to promote BIM understanding, regulate BIM implementation or mandate BIM requirements. These publications encapsulate extensive BIM-focused knowledge; collate significant domain expertise; and represent a substantial effort within the BIM domain. To assist in identifying NBPs, the authors employed explicit ontological structures from the BIM Framework (Succar, 2009) as represented in Figure 1 below:

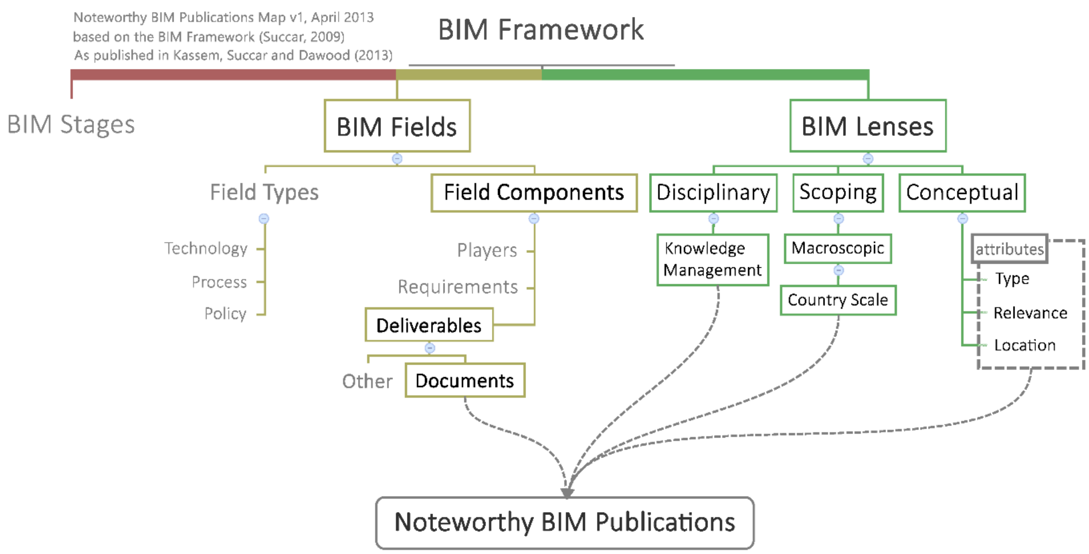


Figure 1: Conceptual derivation of Noteworthy BIM Publications using the BIM Framework

The BIM Framework and its ontological structures are intended to organize domain knowledge and facilitate its understanding. Figure 1 explores how noteworthy BIM publications are derived from the interaction of BIM fields and BIM lenses:

- NBPs are documents (i.e. not websites, blogs or similar);
- NBPs reflect BIM knowledge (i.e. publications focused on BIM skill are excluded);
- NBPs are the deliverables of BIM players (i.e. publications delivered by players from other industries are excluded);
- NBPs cover relevant BIM topics (i.e. publications covering pre-BIM topics are excluded);
- NBPs are macroscopic (i.e. documents aimed at small groups of practitioners or students are excluded); and
- NBPs are selected and organized by country of origin (i.e. NBPs developed across several countries are excluded - e.g. Inpro-EU[1], IDDS[2] or bSI[3]).

Using these framework-based delimitations, NBPs represent numerous types of published documents spanning industry initiatives, peer-reviewed journals, self-published books and other noteworthy publications. However, for the purposes of targeted analysis, this chapter focuses exclusively on publications developed by governmental bodies, industry associations, research institutions and communities of practice.

1.4 Country Selection

Australia (AU), the United Kingdom (UK) and the United States (US) are selected as sample countries to test BIM maturity metrics. This selection is a reflection of three main criteria: (a) the similarity between their construction markets in terms of applicable technologies and terminology, (b) the availability of reasonably wide BIM adoption surveys (BEIIC, 2010 in Australia, NBS, 2013 in the U.K. and McGraw-Hill Construction, 2012 in the U.S.) and (c) the availability of noteworthy BIM publications. Below are the surveys from across the three countries:

[1] Open Information Environment for Knowledge-Based Collaborative Processes throughout the Lifecycle of a Building, please refer to http://www.inpro-project.eu/main.asp

[2] Integrated Design and Delivery Solutions, please refer to http://www.cibworld.nl/site/programme/priority_themes/integrated_design_solutions.html

[3] buildingSMART International and their varied noteworthy publications, please refer to http://www.buildingsmart.org/

Australia – BIM Adoption Surveys

In 2010, a nationwide survey of architects, engineers, builders, owners and facility managers has been conducted (BEIIC, 2010). Data collected reflected industry's perception of BIM benefits and measured their BIM adoption. The adoption rates reported from a sample of 255 Architects, 44 engineers, 12 contractors, 39 owners, 8 manufacturers and 'other' (facility managers, software vendors, project management) are summarized in Figure 2. The report (BEIIC, 2010) highlighted the widespread adoption of BIM and estimated its impact on the Australian economy to reach $4.8 billion by 2025 (BEIIC, 2010, p. 11).

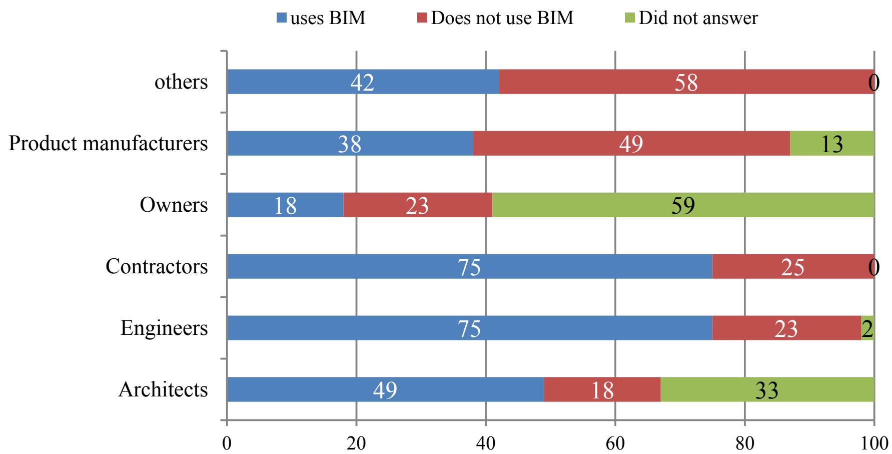


Figure 2: BIM adoption rates in Australia (adapted from BEIIC, 2010)

United Kingdom – BIM Adoption Surveys

In 2013, NBS (2013) conducted a survey including a 1000 professionals across the UK. As shown in Figure 3, the survey did not report its results by discipline but grouped all results as one:

Figure 3: BIM adoption rates in the UK (adapted from NBS, 2013)

United States – BIM Adoption Surveys

In 2012, McGraw-Hill Construction published a survey covering BIM adoption rates across North America (95% of the 582 respondents were from the U.S.) (McGraw-Hill Construction, 2012). Survey results - excluding 10% of sample size (i.e. owners and others) - is reported in Figure 4 below:

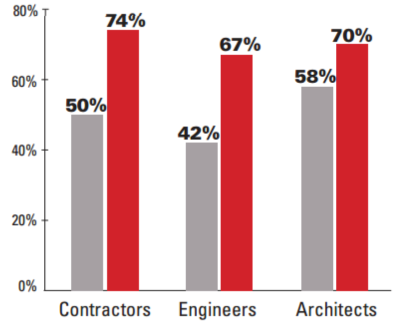


Figure 4: BIM adoption rates in the U.S. (adapted from McGraw-Hill Construction, 2012)

2. THE THREE METRICS

The survey data collated by industry associations provide valuable input into BIM adoption rates across different markets. To augment survey data, this paper proposes three qualitative metrics for measuring country-scale BIM adoption, and by extension, BIM maturity:

Metric 1: the availability of noteworthy BIM publications (NBP)s;
Metric 2: the distribution of NBPs across BIM Knowledge Content (BKC) labels and clusters; and
Metric 3: the relevance of each NBP across markets.

2.1 Metric 1: availability of NBPs

Noteworthy BIM publications (NBP)s are publically-available industry documents incorporating guidelines, protocols and requirements focusing on BIM deliverables and workflows. These publications are the product of various governmental bodies, industry associations, communities of practice and research institutions, intended to facilitate BIM adoption, and realize BIM's value-adding potential. The 'availability' of noteworthy BIM publications is proposed here as an indicator of a country's BIM maturity, a concept derived from other disciplines. For example, in e-Government research, the lowest level of maturity is 'availability' – the online presence - of government documents (Accenture, 2004). Similarly, the World Bank uses availability and number of online documentation as an indicator of a country's e-Government maturity (APEC, 2004). Another example, e-Commerce maturity identifies documentation availability as a maturity indicator (KPMG, 1997). Based on these two examples, this paper adopts a similar approach and identifies the *availability of country-specific NBPs as an indicator of that country's BIM maturity*. In this respect, Table 1 below collates several NBPs that can be used as BIM maturity indicators:

Table 1: Availability of NBPs – Metric 1

Code	Document title	Issuer Type[4]	Issuer, Year
AU 01	CRC-CI National Guidelines for Digital Modelling + Case Studies (2 documents)	RB	CRC-CI, 2009
AU 02	Digital modelling and the built environment, department of Innovation Industry, Science and Research	GD	DIISR, 2010
AU 03	Productivity in the buildings network: assessing the impacts of Building Information Models, report to the Built Environment Innovation and Industry Council	IB	BEIIC, 2010
AU 04	NATSPEC National BIM Guide and Project BIM Brief template	IB	NATSPEC, 2011
AU 05	BuildingSMART Australasia, National Building Information Modelling Initiative	IB	buildingSMART, 2012
AU 06	BIM in Practice, an initiative by the Australian Institute of Architects and	IB	AIA-CA, 2012

[4] RB: Research body, GD: Governmental department, CP: Community of Practice, PI: Private industry, IB: Industry body, LA: Local authority

Code	Document title	Issuer Type[4]	Issuer, Year
	Consult Australia		
AU 07	BIM-MEP AUS initiative by the Air Conditioning and Mechanical Contractors' Association of Australia (AMCA)	IB	AMCA, 2012a
UK 01	Building Information Model (BIM) Protocol - Standard Protocol for use in projects using Building Information Models, CIC/BIM ProFirst Edition 2013	IB	CIC, 2013
UK 02	AEC (UK) BIM Protocol Implementing UK BIM Standards for the Architectural, Engineering and Construction industry - Updated to unify protocols outlined in AEC (UK) BIM Standard for Revit and Bentley Building Version 2.0 September 2012	CP	AEC, 2012
UK 03	Soft Landing Strategy	GD	Cabinet Office, 2012
UK 04	Government Construction Strategy	GD	Cabinet, 2011
UK 05	BIM Management for value, cost & carbon improvement, report number URN 11/948 - A report for the Government Construction Client	GD	DBIS, 2011
UK 06	CPIx BIM assessment form	IB	CPC, 2011
UK 07	Building Information Modelling - an introduction for house builders	IB	NHBC Foundation, 2013
UK 08	Refurbishment resource efficiency case study: Manchester Central Library	IB	WRAP, 2010
UK 09	National BIM Report 2013	PI	NBS, 2013
UK 10	First Steps to BIM March 2013 Competence A Guide for Specialist Contractors	GD	NSCC, 2013
US 01	GSA BIM guides series	GD	GSA, 2007
US 02	Integrated project delivery: a guide	IB	AIA, 2007
US 03	Contractor's Guide to BIM	IB	AGC, 2006b
US 04	National building information modeling standard - version 1.0 - part 1: overview, principles and methodologies	GD	NIST, 2007
US 05	BIM user guides	GD	USCG, 2005
US 06	BIM guidelines	LA	NYCDDC, 2012
US 07	State of Ohio Building Information Modeling protocol	LA	OHIO DAS, 2010
US 08	Planning Guide for Facility Owners– Version 1.0	RB	PennState, 2012
US 09	E203: Building Information Modeling and Data Exhibit	IB	AIA, 2012a
US 10	G Document 201: Project Digital Data Protocol Form	IB	AIA, 2012b
US 11	G Document 202: Building Information Modeling Form	IB	AIA, 2012c
US 12	Consensus Docs 301 BIM Addendum	IB	ACGA, 2006
US 13	Building Information Modeling: A Road Map for Implementation To Support MILCON Transformation and Civil Works Projects within the U.S. Army Corps of Engineers	GD	USACE, 2006
US 14	Building Information Modeling (BIM) Roadmap Supplement 2 – BIM Implementation Plan for Military Construction Projects, Bentley Platform	GD	USACE, 2011
US 15	BIM Project Execution Planning Guide and Templates – Version 2.0 BIM Project Execution Planning	RB	Penn State, 2010
US 16	Construction Operations Building Information Exchange (COBIE): Requirements Definition and Pilot Implementation Standard	GD	USACE, 2007
US 17	USACE BIM Minimum Modeling Matrix (M3) V1.0	GD	USACE, 2012
US 18	The Business value of BIM in North America: Multi-Year Trend Analysis and User Ratings (2007-2012)	PI	McGraw-Hill Construction, 2012
US 19	NISTIR 7417 General Buildings Information Handover Guide: Principles, Methodology and Case Studies	GD/CP	NIST and FIATECH, 2007
US 20	IPD Case Studies	IB / RB	AIA & University of Minnesota, 2012

2.2 Metric 2: distribution

This metric reports BIM maturity in terms BIM Knowledge Content (BKC) distribution across noteworthy BIM publications. BKC is a specialized taxonomy with several classifications. The main classification identifies three *knowledge content clusters* (guides, protocols and mandates) which are subdivided into eighteen *knowledge content labels* (e.g. report, manual, and contract). As described in Figure 5, the BKC taxonomy and its classifications are derived from the explicit ontological structures of the BIM Framework (Succar, 2009) (Succar, 2013). BKC labels and clusters classify NBPs according to their *actual knowledge content* rather than according to each publication's title or its specific – and sometime conflicting - use of terminology. A succinct definition of the three BKC clusters is provided below:

- **Guides**: documents which are *descriptive* and *optional*. Guides clarify goals, report on surveys/accomplishments or simplify complex topics. Guides do not provide detailed steps to follow to attain a goal or complete an activity;
- **Protocols**: documents which are *prescriptive* and *optional*. Protocols provide detailed steps or conditions to reach a goal or deliver a measureable outcome. While documents within this cluster are prescriptive, they are optional to follow unless dictated within a Mandate (see next cluster); and
- **Mandates**: documents which are *prescriptive* and *dictated* by an authority. Mandates identify *what* should be delivered and – in some cases – *how, when* and *by whom* it should be delivered.

When used to assess NBPs, the three BKC clusters would inform country-scale BIM maturity assessment. For example, a country, with all its NBPs pertaining to a single cluster (e.g. guides – descriptive and optional), would arguably face different implementation challenges to those faced by a country with its NBPs distributed across guides, protocols and mandates.

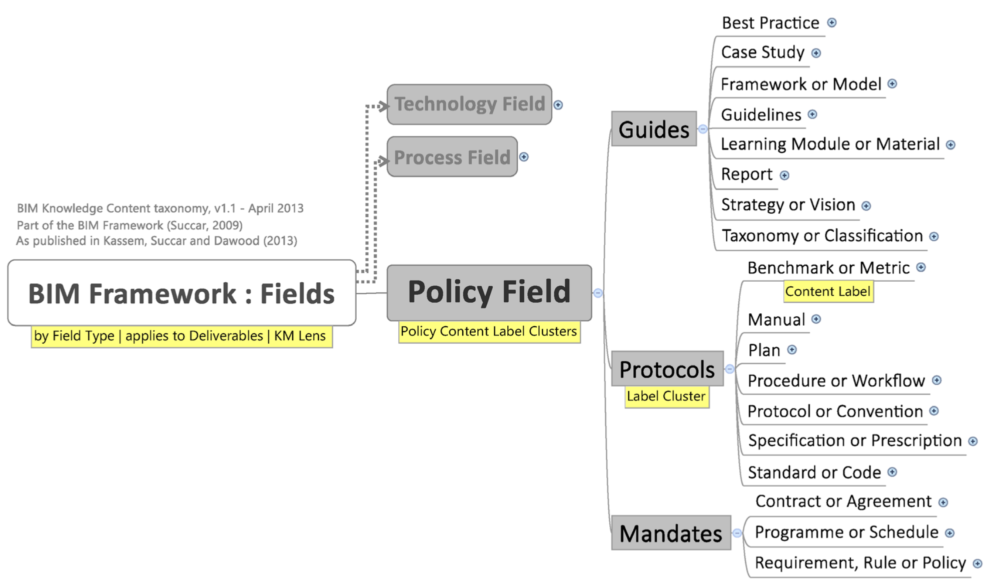


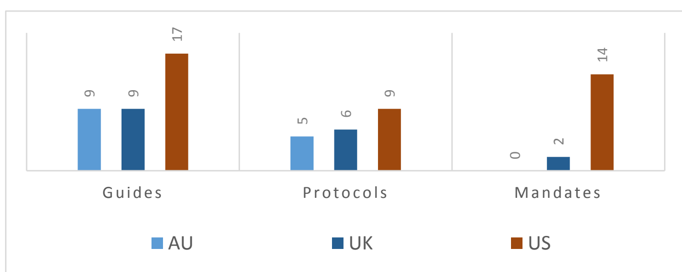
Figure 5: The BIM Knowledge Content taxonomy – Mind Map (Succar, 2013)

BKC clusters and labels (Figure 5) are applied in Table 2 below to classify sample NBPs (refer back to Table 1). Figure 6 also clarifies the distribution of NBPs across clusters:

Table 2: Mapping of NBPs using the BKC taxonomy

		Guides				Protocols				Mandates	
		Case Study G2	Guideline G4	Report G8	Strategy or… G9	Metric or… P1	Manual P2	Procedures or… P4	Specifications … P6	Contract or… M1	Requirement… M3
Australia	AU 01	●	●				●				
	AU 02			●							
	AU 03			●							
	AU 04		●					●			

		Guides				Protocols				Mandates	
		Case Study G2	Guideline G4	Report G8	Strategy or… G9	Metric or… P1	Manual P2	Procedures or… P4	Specifications … P6	Contract or… M1	Requirement… M3
	AU 05			●	●						
	AU 06		●								
	AU 06		●				●	●	●		
United Kingdom	UK 01		●			●				●	
	UK 02		●			●					
	UK 03				●						●
	UK 04				●						
	UK 05			●	●	●		●			
	UK 06					●					
	UK 07						●				
	UK 08	●									
	UK 09			●							
	UK 10			●							
United States	US 01		●							●	
	US 02		●							●	
	US 03		●							●	
	US 04		●		●	●					
	US 05		●								
	US 06					●				●	●
	US 07					●				●	●
	US 08		●								●
	US 09					●				●	
	US 10									●	
	US 11									●	
	US 12									●	
	US 13		●		●						●
	US 14						●	●			
	US 15		●					●			
	US 16								●		●
	US 17					●					
	US 18	●		●							
	US 19	●	●		●						
	US 20	●		●							



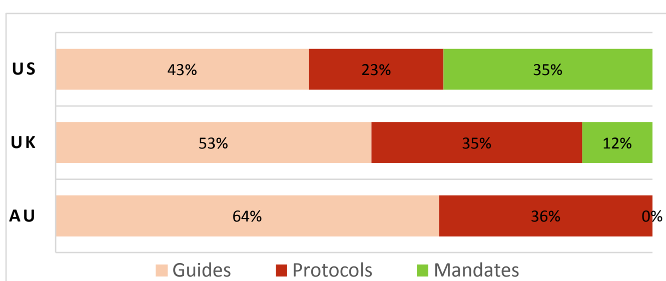


Figure 6: Comparison of labels distribution among countries

2.3 Metric 3: Relevance

Using another classification developed as part of the BIM Knowledge Content taxonomy, NBPs can be assessed according to their level of relevance in comparison to other NBPs across markets. Using this metric, an NBP – noteworthy in its own right - can be measured using a five Relevance (R) index:

R0 - Redundant: the NBP includes out-dated information which is no longer usable or useful
R1 - Relevant: the NBP is relevant, current and contains actionable information
R2 - Regarded: the NBP is highly-relevant, well-cited and well-used in comparison to other similar-topic NBPs
R3 - Recommended: the NBP is authoritative and impactful and considered a reference (among other references)
R4 - Requisite: the NBP is the most authoritative document covering a specific topic

The relevance index is used below (Table 3) to compare different NBPs introduced earlier in Table 1:

Table 3: Relevance Metric as applicable to NBPs

	AU						UK										US																			
	AU 01	AU 02	AU 03	AU 04	AU 05	AU 06	UK 01	UK 02	UK 03	UK 04	UK 05	UK 06	UK 07	UK 08	UK 09	UK 10	US 01	US 02	US 03	US 04	US 05	US 06	US 07	US 08	US 09	US 10	US 11	US 12	US 13	US 14	US 15	US 16	US 17	US 18	US 19	US 20
R0																																				
R1	●	●	●						●	●		●	●	●	●	●	●		●		●	●	●	●					●	●				●	●	●
R2						●		●			●							●								●	●	●					●			
R3				●	●		●													●					●						●	●				
R5																																				

The Relevance Metric as applied in Table 3 above is based on the authors evaluation through initial desktop research and their own experiences as researchers and BIM consultants. These evaluations will need to be tested, confirmed, or modified as discussed in the next section.

3. METRIC VALIDATION

This paper proposes a wider-angle approach to assessing the BIM maturity of countries by augmenting data collected through surveys with qualitative assessment of the knowledge deliverables of each country. These metrics are still in the early stages of development and are proposed here to instigate discussion and invite collaboration. The next step the authors will take is to separate between BIM adoption, readiness, capability and maturity metrics. This will be then followed by data collection from subject matter experts as to either confirm, modify or update our initial evaluation of NBPs. Based on feedback received, additional metrics may be proposed and a weighted, scoring system devised and applied to compiled metrics.

4. CONCLUSIONS

There is an increasing number of BIM maturity metrics to assess the performance of individuals, organizations and projects. Of these, only a few metrics can be applied to measure and compare the BIM maturity of countries. This paper proposed a new approach to augment data collected through surveys. The three metrics are supported by a published framework and measure the availability of noteworthy BIM publications (NBP)s, evaluate NBP distribution across BIM knowledge content (BKC) clusters, and establish the relevance of individual NBPs. In addition to assessing country-scale BIM maturity, policy makers and researchers may find benefit in this proposed approach to evaluate NBPs, identify gaps in BIM knowledge content, and highlight areas requiring further research and development.

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PAPER C

BIM in Practice - BIM Education, a Position Paper by the Australian Institute of Architects and Consult Australia

Succar, B., Agar, C., Beazley, S., Berkemeier, P., Choy, R., Rosetta Di Giangregorio, Donaghey, S., Linning, C., Macdonald, J., Perey, R., & Plume, J. (2012). BIM in Practice - BIM Education, a Position Paper by the Australian Institute of Architects and Consult Australia.

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BIM Education

E Education

E

BIM IN PRACTICE

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BIM Education

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PREFACE

Building Information Modelling (BIM) is a transformative approach to designing, constructing and operating the built environment. BIM includes a wide range of concepts, tools and workflows which need to be learned and applied by industry stakeholders. BIM Education represents the process of acquiring the necessary knowledge and the required skills to generate BIM deliverables and satisfy their respective requirements.

The documents gathered here stem from the efforts of the BIM Education Working Group (EWG). The EWG started its six month mandate back in December 2011 and included 11 members, equally split between industry (practicing professionals) and academia (university/TAFE lecturers and researchers).

There are three documents in the BIM Education section. Read together, they represent the position of the EWG, an invitation for an open discussion, and a foundation for further work. Read separately, each document covers a specific aspect of our work:

– **Document E1** introduces BIM Education, the group's objectives and the structure underlying this effort. It also identifies BIM Learners and their varied requirements

– **Document E2** identifies BIM Learning providers and the current status of BIM Education

– **Document E3** introduces the BIM Learning Spectrum and a draft Collaborative BIM Education Framework

At the conclusion of each document, a summary set of BIM Educational Principles (EP)s is provided. These 20 principles highlight the group's position and provide opportunities for future discussions covering:

– **why** BIM Education is the shared responsibility of industry and academia

– **what** needs to be done to identify the BIM learning requirements of all construction industry stakeholders

– **where** best to start in a suitably comprehensive BIM learning approach

– **who** needs to participate in defining, developing and delivering BIM education

– **how** best to convert BIM educational principles into BIM learning opportunities

– **when** a BIM education mechanism can be instigated to deliver BIM learning dividends

The BIM Education working group hopes this effort resonates well with all those who stand to benefit from a collaborative approach to BIM Education. We also hope the three documents, the framework and the embedded principles instigate a fruitful discussion between - and within - industry and academia.

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BIM Education

E1 BIM Education & BIM Learners

E1

BIM IN PRACTICE

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E.1 BIM Education & BIM Learners [Version 1 – August 2012]

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INTRODUCTION

BIM is a wide array of evolving technologies, processes and policies. Identifying how to best teach or learn about BIM is still being explored by a great number of industry stakeholders. After much discussion, the BIM Education Working Group (EWG) adopted two complementary objectives. The first objective is to deliver a **Collaborative BIM Education Framework**. The second is to deliver a **BIM Education Position Paper** (this document) which describes the working group's position. Both objectives aim to:

- instigate an in-depth discussion with both academia and industry
- connect with other groups, both in Australia and internationally, engaged in developing complementary educational deliverables
- lay foundations for further work by AIA/Consult Australia and their future BIM Education partners

With the limited time and resources available to this Group, we've chosen to focus on identifying a foundational part of the Collaborative BIM Education Framework – defining the BIM Learning Spectrum (refer to **E3 – BIM Learning Spectrum** as part of this series of documents).

UNDERSTANDING BIM EDUCATION

BIM Education is the process of learning[1] the sum of conceptual and practical knowledge relating to BIM technologies, workflows and protocols. Underlying BIM Education are many technical (eg, data management), procedural (eg, team collaboration) and regulatory topics (eg, risk management). These topics need to be:

- integrated within educational curricula
- made readily available to practicing professionals

Such a broad **BIM Learning Spectrum** would serve current professionals, future professionals (current students) and the teachers/trainers who educate them (collectively referred to as **BIM Learners**).

1 Refer to Bloom's Taxonomy (http://en.wikipedia.org/wiki/Bloom's_Taxonomy) for a wide definition of learning and learning objectives.

WHY IS BIM EDUCATION IMPORTANT?

BIM Education is an effort that ranges from spreading basic awareness about BIM risks and benefits to solidifying specialist BIM knowledge and skills. BIM Education facilitates collaboration between project participants of all disciplines – and across all project lifecycle phases. BIM Education is the main communication method to spread technology-enabled, process-driven and policy-encouraged advances in design, construction and operation of facilities. It empowers current and future generations of industry practitioners to achieve increases in productivity, reduction in waste and fulfilment of an aesthetic and sustainable future.

As discussed in several national reports and international guides – refer to the *National BIM Initiative*[2], *BIM in Australia Report*[3] and *Impacts of Building Information Models*[4] – BIM Education is a foundational activity, a critical need for both industry and academia, and a priority due to the apparent skill shortage in this sector in Australia.

BIM plays a key role in facilitating more effective collaboration across disciplines during the full lifecycle of a building project. This relies on accurate exchange of 3D model data and associated information, either through the use of compatible proprietary software applications or the use of an open BIM standard like Industry Foundation Classes (IFC). At present this is based on file exchange, but in the future it is clear that shared BIM database servers will play a more significant role in supporting collaborative processes. This leads to a growing need for industry practitioners to be educated about collaborative work practices and processes that make use of BIM technologies. This should become a core component of professional design and construction education. It follows that Collaborative BIM Education is best developed in a cooperative manner involving all stakeholders, whether universities, TAFE, professional training associations, accreditation bodies and AEC organisations (referred to collectively as the BIM Learning Providers).

The BIM Education Working Group strongly believes that there is a great opportunity for academia and industry to work together to develop BIM curricula that reinforce the value of BIM within the collaborative work practices. We see that a cooperative approach to developing and delivering BIM Education to students and professionals would be a great benefit to the industry.

2 The National Building Information Modelling Initiative: *Volume 1 Strategy - A report for the Department of Innovation, Industry, Science, Research and Tertiary Education*, (2012) prepared by buildingSMART Australasia, but at the time of writing, not yet released publicly.

3 BIM in Australia, a report prepared by Star Monde on behalf of AIA/Consult Australia who conducted a number of BIM/IPD forums across Australia in October/November 2010

4 *Productivity in the Buildings Network: Assessing the Impacts of Building Information Models* prepared by the Allen Consulting Group and submitted to the Built Environment Industry Innovation Council (BEIIC) in October 2010

WHO IS A BIM LEARNER?

BIM technologies and workflows affect all those involved in the design, construction and operation of facilities, ranging across design professionals, managers and tradespeople. In this position paper, we refer to all those who want to learn about Building Information Modelling – in its widest definition – as BIM Learners.

BIM Education focuses on individual learning as opposed to organisational learning. This distinction is important as most BIM guides and national workshops focus on standards, legal implications and success stories. With the exception of training focused on technical tasks, the learning needs of individual users in the midst of this BIM-led industry transformation are not well supported. This is specifically true for a great number of individuals within both industry and academia.

Within industry

- Employees of small organisations with small training budgets – these individuals will have to depend on unstructured learning from ad-hoc sources (eg, learning from internet postings, attending user-led groups, etc).
- Employees of single-discipline organisations – these individuals will need structured guidance to develop and extend their collaborative BIM skills.
- Team managers and project leaders who require – due to the nature of their roles – adequate BIM knowledge in how to manage the deliverables of staff under their guidance.
- Managers and senior managers who are tasked with leading their organisations through the ever-changing BIM landscape.

Within academia

- Students of universities/TAFE institutions who are yet to embrace BIM Education – these students may want to prepare themselves for a working environment where data-rich models and multidisciplinary collaboration is fast becoming the norm rather than the exception.
- Lecturers within universities/TAFE institutions who are yet to embrace BIM Education – these lecturers may wish to expose themselves and then their students to BIM tools and workflows.
- Deans, heads of schools and directors who are tasked with leading their schools and departments – in response to industry's requirements – to keep abreast of collaboration technologies and workflows.
- Accreditation boards which are tasked with reviewing and accrediting universities/TAFE courses and programs.

The above simplified list highlights the varied nature of BIM Learners and their equally varied requirements. In essence, every individual who needs BIM technologies, workflows and protocols within any construction sector, at any position or role, or within a university, TAFE or AEC organisation, is a potential BIM Learner.

CONCLUSION

The accelerating proliferation of BIM within the Construction Industry prompts current and future professionals to continuously learn new technologies, workflows, and protocols. Industry stakeholders – whether they are professionals, academics or tradespeople – need to unceasingly match their knowledge and skills with evolving market requirements. All need to learn and all need to educate others.

BIM Learning includes all those affected by BIM concepts and tools; whether they are students or teachers within tertiary institutions; professionals within AEC organisations; or tradespeople on the job site. BIM Education is the sum of all these individual learners, the BIM topics they need to learn and the learning materials they require.

Summary

EP1. *BIM Education is the shared responsibility of academia and industry*

EP2. BIM Education addresses the requirements of current professionals (irrespective of formal qualification), future professionals (students) and their teachers/ trainers

EP3. BIM Education encompasses all modes of BIM Learning (tertiary courses, industry workshops, online media and on-the-job training)

EP4. BIM Education ranges from spreading awareness to developing highly specialised skills

EP5. BIM Education should be made available to all those who need it in formats which are mindful of their respective disciplines, specialities, roles, education and experience levels

EP6. Collaborative BIM Education should be developed and delivered collaboratively

EP7. Every individual within the construction industry is a potential BIM Learner, and every BIM Learner is a potential BIM Learning Provider

BIM Education

E2 BIM Learning Providers

E2

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BIM Education

E2 BIM Learning Providers

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E2 BIM Learning Providers [Version 1 – August 2012]

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INTRODUCTION

BIM Learning Providers are all those who provide BIM Education, training and development: universities, TAFE, professional associations, Architecture, Engineering, Construction (AEC) organisations, registered training organisations, etc. The working group conducted an initial investigation into the current status of BIM Education within academia and across professional associations. Below is a summary of the findings which influenced this position paper:

BIM EDUCATION WITHIN ACADEMIA – UNIVERSITIES

A recent study – coupled with a literature review and international interviews[1] – indicated that most universities are yet to run fully collaborative BIM courses between students of the three AEC disciplines. However, there is an increasing number of universities around the world who are (a) either currently investigating BIM Education or (b) have actively initiated a BIM-focused, multidisciplinary educational curriculum at undergraduate and/or graduate levels.

In recent months and years, BIM concepts and tools have gradually started appearing within tertiary institutions (especially within graduate programs[2]). In Australia, three universities (the University of Technology in Sydney, the University of South Australia, and the University of Newcastle) are currently involved in Code BIM: Collaborative Design Education using BIM[3] – an Office of Learning and Teaching (OLT) project that aims to develop collaborative programs between AEC disciplines using BIM technologies and processes.

Introducing BIM Education into academia is a difficult change process and – like any major change process – it is likely to encounter resistance. Some of the reported difficulties include:

1. The difficulty of introducing new topics into an already crowded curriculum.
2. Unfamiliarity of lecturers with BIM and other fast-paced technologies and workflows.
3. Reluctance of some lecturers to alter established teaching methods coupled with an unwillingness by some to retrain in new topics.
4. Inability to bridge the traditional educational silos of architecture, engineering and construction and deliver collaborative courses and programs.

BIM EDUCATION WITHIN ACADEMIA – VOCATIONAL EDUCATION AND TRAINING

BIM has a potentially significant impact on the vocational education and training (VET) sector[4] – the sector responsible for training and retraining construction industry's tradespeople (carpentry, plumbing, painting, electrical, etc) and para-professionals (architectural technology, building design, surveying, etc). VET covers a range of qualifications from Certificate II (AQF 2)[5]up to Advanced Diploma (AQF 6). All of these VET qualifications, the industry roles they represent and the education they require, are significantly affected by BIM technologies and workflows.

First, para-professional qualifications (AQF 4-6) have traditionally generated technician level graduates within a wide range of discipline areas. With the advent of BIM technologies, many have taken the opportunity to develop into BIM specialists within their respective fields and currently play diverse and increasingly important roles. A great number of modellers, model managers, BIM project coordinators and BIM managers have their roots in para-professional education. Also, in addition to the knowledge and skills para-professionals need to operate within their chosen specialities, VET trainees must now learn how to use data-rich models and other technologies to collaborate with their peers, tradespeople, and AEC professionals. New BIM-focused courses now need to be developed to ensure para-professionals are 'industry ready' at graduation – courses which necessarily include hands-on, collaborative and multidisciplinary project work.

Second, at trade qualification levels (AQF 2-3), the increasing availability of accurate, information-rich models is starting to impact the construction site. While many in the steel detailing and mechanical ducting professions have been using 3D CAD for many years (especially for offsite prefabrication), BIM has highlighted the need for a tighter coordination between many trades and specialties. This in turn has dramatically increased the need for highly trained technicians with additional experience in model interrogation, clash detection, construction sequencing and quantity take-off. These skills should now be included in trade certificate courses so trainees benefit from available BIM technologies and can collaborate efficiently with professionals, para-professionals, product suppliers and others within the construction supply chain.

1 This is based on a recent investigation conducted by Jennifer Macdonald, an EWG member and PhD candidate at the University of Technology, Sydney.

2 For example, refer to BIM Education programmes in the UK: MSc/Dip/Cert *BIM and Integrated Design* (University of Salford - http://bit.ly/LHIetA), and the recently announced *MSc Building Design Management with BIM* (Northumbria University - http://bit.ly/LHIbhe).

3 For more information, refer to University of South Australia, *Code BIM* project page - http://bit.ly/sZFArR.

4 The VET sector includes Training and Further Education (TAFE) institutions, Registered Training Organisations (RTO)s, Continuing Professional Development (CPD) providers.

5 The Australian Qualifications Framework (AQF) is 'the national policy for regulated qualifications in Australian education and training. It incorporates the qualifications from each education and training sector into a single comprehensive national qualifications framework.' For more information about the Australian Qualification Framework, please visit http://www.aqf.edu.au/.

BIM EDUCATION WITHIN INDUSTRY – PROFESSIONAL ASSOCIATIONS

Professional associations can play an important role in promoting BIM Education within both academia and industry. Some of these associations provide course accreditation, certification and/or Continuing Professional Development (CPD) programs.

To develop a better understanding of the attention professional associations give to BIM Education, the EWG conducted an introductory investigation (online and phone interviews) covering 12 associations. From this initial investigation – which focused on CPD programs - we learned the following:

1. Eleven of the 12 associations offer Continuing Professional Development (CPD) courses to their members. Of these, most indicated an awareness of BIM, three indicated that they include BIM in their learning activities (presentations by guest professionals), and one association reported that they currently offer BIM-specific training as part of their CPD program.
2. Most professional associations seem to have adopted a wait-and-see approach. Some are learning from each other – especially from those who have recently developed a BIM-focused set of deliverables and most indicated a keen interest in learning more about BIM Education.

BIM EDUCATION WITHIN INDUSTRY – ORGANISATIONAL TRAINING

BIM training within organisations is another important aspect of BIM Education. Driven by immediate business benefit, many design, construction and operation companies offer their staff the necessary training to generate and share data-rich models with their project partners. Training offered – whether on-the-job or through registered training organisations – is mainly technical, focused on cultivating the skills necessary to use BIM's ever expanding repertoire of tools and workflows. However, other types of training are less frequently provided-training which targets the soft skills necessary to manage multidisciplinary teams and deliver collaborative BIM projects (eg, team management skills, meeting facilitation, conflict resolution).

While some organisations prefer to offer their own customised, in-house BIM training, many would argue (especially those with limited training budgets) for integrating BIM Education/training within universities so students are industry-ready by the time they enter the employment market. Others would also argue that professional associations should make available non-technical BIM training for managers and senior staff (eg, project leaders, team managers). Such training is not available on demand but through irregular BIM-focused conferences and workshops.

CONCLUSION

There are many stakeholders involved in the provision of BIM Education. Within academia, universities and TAFE institutions have already started to deliver a range of BIM course offerings. Within industry, professional associations have also started – albeit slowly – to offer BIM leaning opportunities to their members through their varied CPD programs. Driven by market imperatives, AEC organisations have continued to invest heavily in BIM training with a clear focus on developing staff's technical capabilities. In summary, although much progress has been made over the past few years, much effort is still needed to extend BIM education across professional boundaries and to encourage stakeholders to embrace a more collaborative approach to BIM learning and project delivery.

Summary

EP8. BIM adoption within industry and academia is a significant change process (technical, procedural, cultural) which requires a significant investment in systems and people.

EP9. Accreditation and professional associations should engage with universities to develop new collaborative BIM courses or to integrate the principles and technologies of multidisciplinary collaboration into their existing curricula.

EP10. Tradespeople and para-professionals stand to benefit and contribute to BIM and its wide-ranging effect on project lifecycle phases and construction supply chains. The VET sector should incorporate data-rich models and multi-party collaborative workflows into educational curricula and delivery strategies.

EP11. There is need to de-mystify the BIM process and develop integrated, coordinated and viable BIM training modules delivered via professional associations. These training modules should align with university/TAFE curricular and tightly complement their educational deliverables.

EP12. There is a need for BIM-ready graduates. Availability of adequately prepared graduates will minimise (or at least refocus) the training delivered by AEC organisations.

EP13. There is a need for regular BIM Learning opportunities and non-technical BIM learning materials, specifically tailored for senior and executive staff.

EP14. There is a need to consider how to assess and improve the BIM knowledge, skill and experience of current professionals, para-professionals and tradespeople.

BIM Education

E3 BIM Learning Spectrum

E3

BIM IN PRACTICE

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BIM **E**ducation

E3 BIM Learning Spectrum

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E3 BIM Learning Spectrum [Version 1 – August 2012]

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INTRODUCTION

The BIM Learning Spectrum is composed of all BIM topics (technical, operational and managerial), across project lifecycle phases, and specialities. Depending on the perspective adopted, these topics can be identified as learning topics, teaching subjects or individual competencies. This paper adopts the perspective of the learner and will use the term individual **BIM Competencies**[1] to represent the granular elements within the broad BIM Learning Spectrum.

1 BIM Education focuses on individual attainment of BIM skill and knowledge. Every BIM subject matter – if used within the context of educating/training individuals – will be referred to as a BIM competency.

UNDERSTANDING INDIVIDUAL COMPETENCIES

The BIM Learning Spectrum includes all that should be learned about BIM technologies, workflows and protocols. It is the combined list of all learnable BIM subject matter within construction disciplines and roles; the ever-changing sum of individual BIM competencies which industry practitioners and students need to learn.

According to the US Department of Education, a competency is a 'combination of skills, abilities, and knowledge needed to perform a specific task'[2]. Using this definition as a base, a BIM Competency is the combination of conceptual knowledge, BIM skills (practical knowledge) and experience necessary to perform a BIM-related task.

2 Refer to Defining and Assessing Learning: Exploring Competency-Based Initiatives (2001), the US Department of Education; National Center for Education Statistics, page 1. Note that the Australian Qualification Framework (AQF) indirectly defines the term competency as follows 'Training Packages use competency standards to describe the skills and knowledge needed to perform effectively in the workplace' – refer to AQF Certificate I Guidelines.

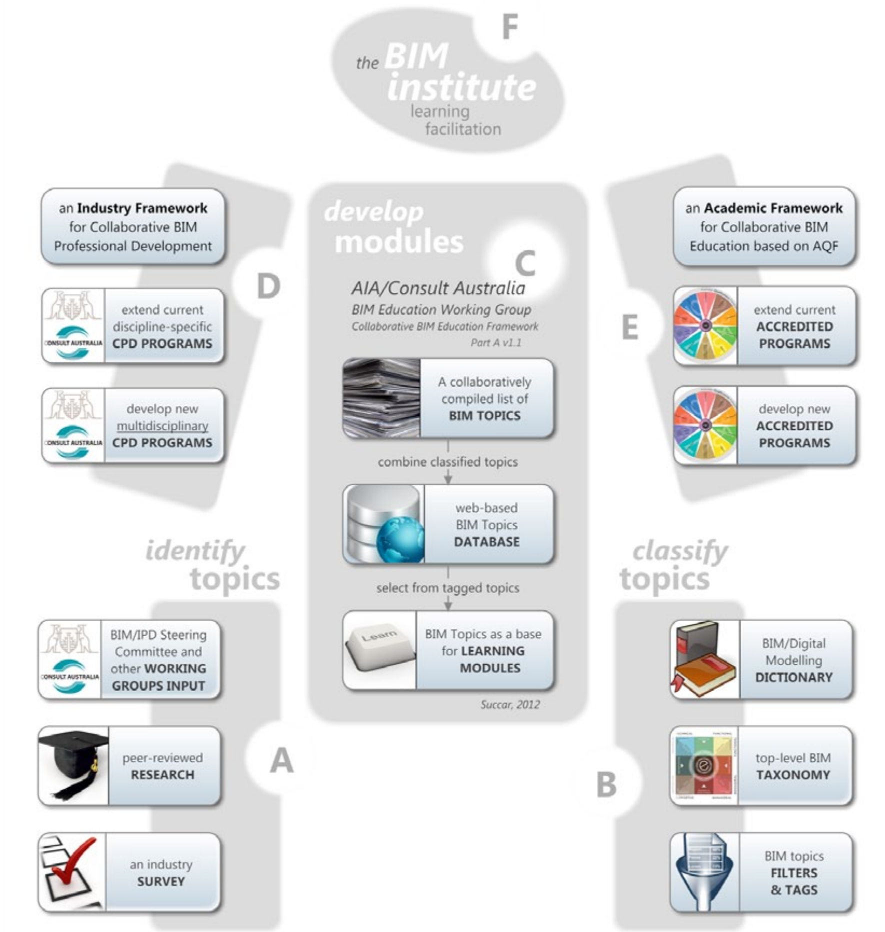

Figure 1. Collaborative BIM Education Framework Part A v1.1

There are hundreds or even thousands of BIM Competencies which can be learned by individuals involved in the design, construction and operation of the built environment. These individuals range in their position of responsibility and role within the construction supply chain. For example, an architect implementing a spatial program within a hospital model will require a different set of competencies from an engineer performing thermal analysis on those spaces. Also, the competencies needed by a junior modeller during their day-to-day activities are quite different from those required by a team manager responsible for coordinating the efforts of many individuals.

For BIM competencies to be defined in a useful manner, they need to be organised against overlapping criteria: disciplines, specialties, roles and levels of practical experience. Some classifications which can be used to organise BIM Competencies already exist (eg, OmniClass Table 33 – Disciplines) while others need to be specifically developed. In organising competencies, the EWG acknowledges that:

1. Some BIM Competencies will be applicable across several disciplines and roles while other competencies will be specific to a single discipline or role.
2. The same BIM Competency may be delivered and measured differently by each BIM Learning Provider. A university may, for example, use Bloom's taxonomy as a basis to deliver and measure student learning, while an AEC organisation may use a simpler three or five-scale model. To account for this variation between different BIM Learning Providers – and particularly between academia and industry – the process of identifying BIM topics or competencies should be kept separate from the process of measuring them.

DEFINING THE BIM LEARNING SPECTRUM

The Collaborative BIM Education Framework intends to generate discussion within and between industry and academia. As a first step towards generating a comprehensive approach, this paper introduces a partial framework (refer to Figure 1) subdivided into six main components:

Component A. Identifying BIM Competencies

The framework highlights three main ways to identify BIM Competencies:

- A seed set of BIM Competencies has already been identified by this Working Group[3].
- BIM Topics and Competencies will be identified through reviewing peer-reviewed literature, benefiting from relevant educational frameworks (refer back to Document E2 – 2.1 & 2.2), and surveying the educational requirements of participating institutions.
- BIM Topics are identified through a survey, a set of workshops and discussions with industry and by harvesting the knowledge of different groups through their representative associations.

Component B. Classifying BIM Competencies

For BIM Competencies as a basis for BIM Education, they should be clearly and consistently defined:

- A BIM dictionary to clarify BIM terms and acronyms across all topics. It will structure the syntax governing BIM Competencies (how a competency is named, defined, abbreviated, etc).
- A top-level taxonomy (a classification) to organise all BIM Competencies under a single hierarchy. This is important to collect all current and future learning topics in one structured list.
- A number of BIM labels (eg, role groups, disciplines, difficulty levels, delivery modes, etc) to organise BIM Competencies against several criteria (a faceted classification).

This may be better understood by referring to the sample table following:

3 A list of seed individual BIM Competencies may be published online at a later stage. Please visit the BIM Education page on the AIA/Consult Australia website - http://bim.architecture.com.au/.

BIM TOPICS (competency)	TAXONOMY (competency class)	TAGS or LABELS					
		Discipline	Sector	Speciality	Role Group	Difficulty	Delivery
Understanding Typical BIM Collaboration Workflows	F (Functional)	33 (all disciplines)			2 (Team Managers and Project Leaders)	3	Online Video
Legal Implications of Using Models as a Primary Source of Design Information	A (Administration)	33-21 (Design)	All		1 & 5 (Operational Management and External Service Providers – Legal)	4	Online Video, Workshop, Pamphlet
Developing and Managing Object Libraries	I (Implementation)	33-21	All		4 (BIM Managers)	2	Workshop

TAXONOMY: the sample used here includes nine mutually exclusive classes. Each BIM Topic can exist under one class only.

TAGS: each BIM Topic can be tagged indefinitely. Tags are flexible, non-exclusive labels which are used to organise and then filter competencies. **Discipline, Sector and Speciality** are tags based on OmniClass Table 33 (listed as Title Level 1, 2 and 3 respectively – Title Level 4 is not used here). OmniClass is an open standard developed by the Construction Specifications Institute (CSI). **Role Group** is a sample taxonomy to identify target audience based on their organisational roles. **Difficulty Level** is a sample scale applied to each BIM topic to indicate prerequisite levels of knowledge, skill, and experience (e.g. Difficulty Level 1 topics focus on 'BIM awareness' and have no prerequisites). **Delivery Mode** identifies the recommended format(s) for delivering a BIM topic to a target audience.

Tabel 1.

BIM Learning Modules (Target Audience)	**BIM Topics Included** (Competency Class)	**Delivery Level** (Delivery Method)	**Prerequisites**	**Optional Tags**
BIM Project Facilitation (Project Managers, Clients, Facility Managers)	**Developing a BIM Management Plan** (Implementation)	**Level 1** (workshop)	Understanding BIM Workflows	Workflow Management, Team Management, Conflict Resolution, etc...
	Understanding Data Exchange Protocols (Functional)	**Level 1** (presentation)		
	Understanding Model Progression Specifications (Technical)	**Level 2** (workshop)		
	...Other			
Model Management for Collaborative Projects (BIM Managers, Senior Technical Staff)	**Understanding Data Exchange Protocols** (Functional)	**Level 3** (online presentation)	BIM Managers, Technical	Data Management, Technical Roles, Auditing Protocols
	Model Auditing for Model Managers (Technical)	**Level 2** (lab)		
	...Other			

Tabel 2.

Component C. Collating Competencies & developing BIM Learning modules

The number of BIM Topics required by BIM Learners (refer back to Document E1) is quite large in number. To enable BIM Learning providers and other industry stakeholders to collate and classify BIM Competencies, a dedicated information system is needed. The EWG believes that an online **BIM Learning Hub** – a web-hosted database – is the most efficient way forward. With an adequate database structure and intuitive interface, the Learning Hub will be able to streamline the process of collecting and classifying BIM Competencies.

The online system will also be instrumental in developing **BIM Learning modules** – a collection of BIM Competencies, intended for delivery to a specific audience at a selected level of difficulty. The content and **delivery format** (course, lab, workshop, video) of each learning module depends on which group of BIM Learners are being targeted (an undergraduate student, a tradesperson, a construction manager).

BIM Learning modules can either be standardised (for the purpose of course accreditation) or customised by each BIM Learning Provider to match their constituent members. While all modules use the same BIM dictionary definitions and taxonomy classifications (as discussed in Component B), they can vary significantly in how modules are packaged and delivered to learners:

Component D. An industry framework for professional development

As discussed in Document E2, many organisations and their representative bodies already deliver **BIM Learning and accreditation opportunities** to their staff and constituent members. However, to deliver the needed **Collaborative BIM Training and Development** to current professionals across disciplines and specialities, there is a need to develop a **BIM Education Cooperation Framework** between industry associations. Such a cooperation framework – even if partially subscribed to – will allow the generation and joint delivery of much needed, collaborative BIM Learning modules (in the form of Continuing Professional Development courses or similar). A well-structured and accessible BIM Learning Hub will facilitate such cooperation and allow practitioners to contribute towards and make good use of discipline-specific and multi-disciplinary BIM Learning modules.

Component E. An academic framework for BIM Education

Tertiary institutions are facing specific challenges as they adopt ever-changing BIM technologies and multidisciplinary workflows (refer back to Document E2). Specialised academic frameworks for BIM Education will be needed to enable academic institutions to contribute to and benefit from the BIM Learning Hub. Such frameworks exist today (eg, the OLT project identified in Document E2) and can play an important role in aligning the deliverables of this collaborative framework with the specific requirements of tertiary education. Jointly identified and developed BIM Learning modules – customised for university lecturers or graduate/undergraduate students – can play an important role in facilitating the introduction of BIM topics into schools and faculties.

Component F. The BIM Institute

The Collaborative BIM Education Framework requires a substantial effort to implement. It also requires a well-coordinated, long-term commitment by industry stakeholders. In alignment with buildingSMART-Australasia's National BIM Initiative, the Education Working Group acknowledges the need for an organised effort – a National BIM Institute, BIM Academy or similar – to facilitate the development and delivery of BIM Education across industry[4]. The education-focused tasks assigned to such an institute should be collaboratively defined by all BIM Learning Providers – but may well include:

- Develop and maintain classification systems for organising BIM Education
- Develop and maintain the BIM Learning Hub
- Develop a coordination framework between professional associations for the purpose of multi-disciplinary BIM training and development
- Initiate BIM collaboration labs for sharing knowledge and testing new workflows
- Conduct BIM-usage surveys and publish relevant papers and reports
- Act as a central social space for all BIM Learners and BIM Learning Providers

To reiterate the importance of the Collaborative BIM Education Framework introduced above, the three BIM facets (the BIM Leaner, the BIM Learning Provider and BIM Learning Spectrum) are combined into a simplified yet typical scenario:

> Each BIM Learning Provider (a university, TAFE, professional association) has (a) a unique interest, ability and approach in delivering (b) a selected part of the whole BIM Learning Spectrum to (c) a targeted subset of BIM Learners.

4 Such an institute will have many other objectives beyond BIM Education (eg, lobbying, communication, etc)

> For example, a professional association (a Learning Provider) representing cost planners may be interested in delivering a CPD Program to their members (cost planners – a type of Learner) titled 'IPD from a Cost Planning Perspective' (a BIM Topic within the overall Learning Spectrum). However, the same professional association may not be well placed or interested in delivering other topics needed by the same learners. For example, 'Cost Estimation for Algorithmic Structures' and 'Cost-Estimation using [Software Name]' are better delivered through a tertiary course and a registered, online training video respectively.

Using the example above, it is in all stakeholders' interest to participate in a Collaborative BIM Education program which allows them to focus on developing their unique abilities and rely on other Learning Providers to deliver the complementary BIM topics needed by their constituents.

CONCLUSION

The BIM Learning Spectrum includes all topics that need to be learned by various BIM Learners – irrespective of their discipline, role or formal qualification. At the core of the BIM Learning Spectrum are thousands of individual BIM competencies – the granular learning topics underlying the many discipline, sectors and trades. Using a specialised taxonomy, these individual competencies can be collated into BIM Learning Modules, each customised to match the requirements of their target audience. The BIM Education Framework, introduced in this paper, proposes how to identify, organise and collate these competencies and modules. It also identifies two additional and complementary frameworks intended to encourage the proliferation of collaborative BIM education across professional associations and academic institutions. The framework finally proposes the formation of a BIM institute, an entity which can play an important role in promoting and facilitating BIM learning throughout industry and academia.

Summary

EP15. There are many BIM competencies which need to be learned by individuals involved in the design, construction and operation of facilities

EP16. A collaborative CPD program is an integral part of the Collaborative BIM Education Framework.

EP17. A web-hosted, socially connected BIM Learning Hub at the core of the Collaborative BIM Education Framework is needed.

EP18. A BIM Learning Module is a collection of BIM topics, customised for a target audience, and delivered at a defined level of difficulty.

EP19. An academic framework informed by research, discipline professionals and other industry stakeholders is a pre-requisite for delivering Collaborative BIM Education within tertiary institutions.

EP20. The establishment of a well-structured and well-funded BIM institution is essential to facilitate the development and delivery of Collaborative BIM Education across the construction industry

PART III
APPENDICES

This thesis by publication includes six appendices: Appendices A and B include two foundational knowledge structures developed as part of this study yet partially used within published papers; Appendix C lists citations received to published works to date to indicate potential impact achieved to date; Appendix D includes the focus group's information sheet and feedback form used during primary data collection; Appendix E includes 'statements of contribution' for papers A1, A5, A6, B1, B2 and C; and Appendix F includes a compilation of all bibliographic references cited within the introduction document, submitted papers and appendices.

APPENDIX A

The BIM ontology

Appendix A: the BIM ontology v2.0

Building Information Modelling: conceptual constructs and performance improvement tools

Introduction

The BIM ontology is an informal, semi-structured, domain ontology intended for knowledge acquisition and communication between people. It is intended to represent knowledge interactions (push/pull) between BIM players, their deliverables and requirements (Figure 1) as described within Papers A1 and A2 (Succar, Sher, & Aranda-Mena, 2007) (Succar, 2009).

The BIM ontology includes BIM-specific concepts, their relations and attributes facilitate analysis of domain knowledge (Noy & McGuinness, 2001), enable the construction of a domain framework (Studer, Benjamins, & Fensel, 1998), and support knowledge acquisition and communication (Milton, 2007a; Milton, 2007b) (Cottam, 1999) (Studer et al., 1998). Figure 1 below illustrates how ontological objects underlie the BIM Framework. The *concept map* (Figure 1 - right) is a visual representation of the ontological relationship between the three concepts (BIM Fields, BIM Stages and BIM Lenses); while the *visual knowledge model* (Figure 1left) abstracts these relationships into the *Tri-axial Model*, a simplified graphical representation to facilitate communication. As discussed in Papers A1 and A2, this combination of visual modelling driven by explicit ontological relations renders the BIM Framework and its many conceptual constructs more accessible for analysis, modification and extension.

Also, as depicted in Figure 7 (Part I: Introduction Paper), ontological relations enable a 'conceptual mesh' linking different types of *conceptual constructs*: frameworks, models, taxonomies, classifications and specialized dictionary terms.

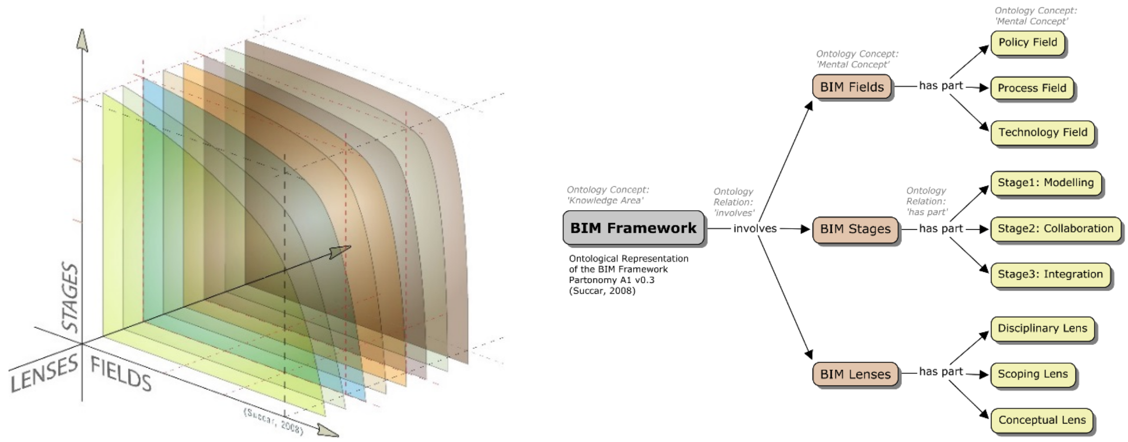

Figure 1. Knowledge model (left) + concept map representing underlying ontological structure (right)

Generating the BIM ontology

The BIM ontology has been generated by amending and reusing existing ontologies; a process recommended by Noy and McGuiness (2001). The reuse of an existing ontology followed Gruber’s criteria for shared ontologies: clarity, coherence, extensibility, minimal encoding bias and minimum ontological commitment (Gruber, 1995). Based on these criteria, the BIM ontology was first derived from the General Technological Ontology (Milton, 2007a) (Milton, 2007b) and the General Process Ontology (Cottam, 1999). While earlier iterations of the BIM ontology followed source definitions, newer iterations are more closely matched with the conceptual and practical requirements of the BIM domain.

Knowledge objects

The BIM ontology comprises of **four high-level knowledge objects**: concepts, attributes, relations and knowledge views (Table 1). Starting with version 1E, the ontology has been expanded to include specific to BIM collaboration and BIM performance assessment.

Table 1. BIM Ontology: Knowledge Objects Summary

Knowledge Objects	Description	Example	Derived From	Original Syntax
Concepts	includes concepts, tasks and task components	People , Products	Extended from GTO	n/a
Attributes	attributes and values to be associated with Concepts	Glossary of BIM terms	Extended from GTO	n/a
Relations	relation between Concepts	'is part of', 'has expertise'	Extended from GTO	n/a
Knowledge Views	a purposeful compilation of Concepts, Attributes and Relations	a generated view or publication	Derived from GTO -modified syntax, different meaning	Home Page

Table 2. Concepts

Concept	Description (if needed)	Example	Derived From	Knowledge Model
Activity	Includes sub-activities, tasks, sub-tasks and steps	Merge models, meet client, design a stadium	New	
Artefact	Physical or digital items acting as clues to or proof of the existence of process or a policy	A Training Log is an artefact proving the availability of a training plan or programme	New	Level of Evidence taxonomy
Capability	The abilities of organizations and teams	Model-based collaboration	New	BIM Capability Stages
Certificate	A formal testimony of capability	A trainer's certificate	New	
Competency	The abilities of individuals and groups	The ability to generate a thermal analysis within an object-based model	New	BIM Competency Taxonomy
Component	Virtual objects	e.g. Revit family, GDL object	New	
Constraints	Limitations and barriers	Capacity, geography, money, time...	GPO modified meaning	
Data Source	Data source	The Australian Bureaux of statistics	New	

Concept	Description (if needed)	Example	Derived From	Knowledge Model
Deliverable	Non-physical products and services	Description, analysis, representation, drawing	New	
Document	A digital or analogue document	A report	New	
Equipment	Machines, vehicles...	A computer, a car	New	
Event	Happenings in a domain wether controlled or not	Training session, a milestone, an accident, a data entry...	GTO	
Example	Illustration of meaning , a representation of a type, an instance	Arup is an example of a company (an org unit	GTO	
Field	A field of enquiry	The BIM technology, process and policy fields	New	BIM Fields
Function	Purpose of a product and/or each its sub-components (applies to objects)	Measures distances, scans documents...	GTO	
Incentive	Drivers for a course of action or inaction	Profit, marketing, publicity, Intellectual property, Efficiency, hr benefits	New	
Knowledge Domain	Domains, sub-domains, disciplines, specialities	Knowledge elicitation	GTO (Knowledge Areas) modified syntax	
Maturity	The quality, repeatability and excellence within capability	Maturity level	New	Maturity Levels
Message	Message	Email message	New	
Metric	A system or standard of measurement	Degree of Certainty	New	
Milestone	A significant and recognizable event; a stage or step along a process	A project milestone	New	
Model use	A deliverable of using 3D models	Augmented reality, construction sequencing, model-based estimation	New	BIM Wheel
Organizational Unit	Markets, industries, disciplines, organizations and parts of organizations	AEC industry, companies, departments, groups, teams	GPO & GTO (Org Units) modified syntax	Organizational Hierarchy

Concept	Description (if needed)	Example	Derived From	Knowledge Model
Place	A location	Melbourne's central business district	GTO (locations) modified syntax	
Player	Those who take action in a specific field (technology, process or policy).	Organizations, individuals or stakeholders	GPO (People) modified name/ meaning	BIM Fields, Field Interactions and Field Overlaps
Product	Assemblies, parts, materials...	A building, a pre-cast panel	GTO (Phys Entities) modified syntax	
Recommendation	An advice aiming to generate or modify action	Modelling best practices	GTO (Advice) modified syntax	
Requirement	Mandatory characteristic	A business or a technical demand	GPO	
Result	Results, conclusions and interpretations	Fail, pass, true, false, continue, return...	GPO	
Roles	Responsibilities of people involved in the domain	Designer, foreman Knowledge engineer	GTO	
Sample	Sample	A tile sample	New	
Social Value	Mechanism and effects occurring in a social context	Respectability, trust worthiness, risk-tolerance, cultural values, innovation, leadership and championship	New	
Space	A built and identifiable enclosed area	Room, floor,	New	
Software	End-user software programs or a bit if code	Word, Revit, Illustrator, CMaps...	GTO (Software) modified syntax	
Tool	A single function physical device (knowledge tools are covered in Knowledge Views, a higher level ontology component)	A screw driver, a shovel…	New	
Trigger	Special events whose occurrence initiates tasks in the domain	Receive a sales order, change in policy...	GTO	
Workbench	A set of complex developmental activities grouped together as workload packages and assigned to specialist working groups	Knowledge Foundations' workbench	New	BIM Excellence Knowledge Infrastructure Workbenches

Table 3. Attributes

Attribute Name	Description	Example	Derived From	Original syntax
Cost	A monetary value expressed in whole numbers, fractions and decimals	$100	New	N/A
Count	An expression of elemental numbers using integers	Number of staff, cars, drawings	GTO - modified syntax	Numeric al
Description	An explanation expressed using words, phrases and sentences	Glossary, Descriptions	GTO - modified syntax	Sentence
Grade	A variables denoting preference or developmental achievement expressed in integers, percentages or text	Importance (High/Low), Priority (1,2, 3), Order (first, second, third,…), Degrees of Relevance, Levels of Maturity	New	N/A
Link	A hypertext connection	A hyperlink, UNC path, email address or similar	GTO - modified syntax and meaning	Hypertex t
Location	The coordinates of an object within a physical space	Geo Tag, x/y/z	New	N/A
Order	An arrangement whether chronological or spatial – not preferential or developmental (refer to Grade)	Project Phases, Organizational Scales	New	N/A
Proposition	A mutually exclusive distinction between clear choices	Left or Right, True or False (or not known)	New	N/A
State	A description of condition whether temporary or permanent	Final submission	New	N/A
Time	An expression of chronology expressed in minutes, second, days, etc…	10 weeks	New	N/A
Type	A differentiation of genus	Gender (male/Female),	GTO - modified syntax and meaning	Categoric al

Table 4. Relations List (version 1E - extended)

Relation	Relation
aborts	interchanges (interoperable exchange)
aggregates	interviews
allows	involves
analyses	joins
appends	knows
approve	leads
audits	links to
authorizes	locates
causes	maintains
certifies	makes
checks	maintains
chooses	manages
classifies	maximises
completes	measures
collaborates with	merges
collates	minimises
collects	models
commissions	monitors
communicates with	occupies
compares	operates
conducts	owns
confirms	participates in
constructs	performs
consults	plans
contacts	populates
contains	prepares
continues	prioritises
controls	procures
coordinates	produces
decreases	provides
delimits	provides for
delivers	pulls (specific to BIM knowledge exchanges)
demolishes	pushes (specific to BIM knowledge exchanges)
demonstrates	qualifies
deselects	quantifies
designs	questions
detects	receives
describes	recommends
develops	regulates
discovers (as in BIM Assessment GLevel 1)	rejects
divides	replaces
discusses with	requires
documents	reviews
educates	revises
empowers	runs
establishes	samples
estimates	selects
exchanges	shares
explodes (for CAD blocks/cells/families)	simulates
evaluates	starts
facilitates	stops
federates	supplies

Relation	Relation
follows	surveys
functions as	tests
generates	tracks
guides	trains
has part	transfer
has resource	transmits
identifies	understands
ignores	updates
implements	uses
increases	validates
informs	warns
initiates	writes
integrates	

Table 5. Knowledge Views (version 2)

Name	Description	Example
Knowledge Document	A *delimited self-contained view* of multiple concepts and their relations - irrespective of *knowledge content format* (text, images or graphs) or *knowledge content medium* (hardcopy or softcopy)	A training manual, a journal article, a CAD drawing, a web-page
Knowledge Model	A *structured view* of concepts and their relations. Knowledge Models includes classifications, taxonomies, ontologies, models, frameworks and theories. Knowledge Models are not self-contained and are typically represented within Knowledge Documents (as a graph, list or matrix) embedded within Knowledge Tools	A concept map, repertory grid, timeline, process map, concept map, flowchart, Gantt chart...
Knowledge Tool	An *interactive view* of concepts and their relations intended to assess, assist and educate its users. A tool has modifiable variables leading to varied outputs based on inputs	A calculator, an online assessment tool, a cad software…
Knowledge Store	A repository of raw data, structured information and Knowledge Documents	A web store, wiki, content management system, database…

Revision history

The Revision Table below lists previous iterations and their change log:

V.	Date	Applies to	Description
1.0	**18 Oct '07**	All	Initial version prepared for Updated Research Proposal
1.1	**8 Mar '08**	Concepts	Organizational Group becomes Organizational Unit – Description broadened to include Markets, Industries, Disciplines and their sub-parts
			Modify description of Recommendation (added intent to generate action)
			Added Deliverables
			Modified examples under Incentives (broadened)
			Added Human Resources
			Modified examples of Information Resources (added graphical and non-graphical databases)
			Modified Places to Locations (broader meaning – reverted to GTO's original term)
			Modified description of Agents (included Organizational Champions and renamed managerial consultant to Industrial Consultant)
			Modified description of Social Phenomena (added innovation & championship)
			Modified Software Tools to Software Applications
1.2	**26 Jul '08**	Concepts	Modified description of Social Phenomena (modified respectability, trust worthiness, risk-tolerance, cultural values and added leadership)
		Attributes	Modified description of Number (added monetary value)
1.3	**10 Jul '11**	Relations	New relations added Some relations modified or removed Relations are presented through a two-column table to represent both active and passive voices
		Attributes	Added Preposition, Relevance, Time, Cost and Location as new or separate Attribute
			Renamed Text to Description, Category to Type
		Concepts	Renamed Actors to Players
			Added Agents
1.4	**17 Nov '11**	Views	Added Knowledge Tools as a new view
		Concepts	Added Artefacts as a new concept
		Relations	Added and modified many relationships
1.5	**24 Mar '13**	Introduction	Modified introductory text
		Versioning	Changed version numbering from alphanumeric to numeric. V1A is now V1.0…V1F is now V1.5
1.6	**9 Jun '13**	Introduction	Updated for submission as an appendix to the PhD thesis
		Relations	Removed passive voice
1.7	**17 Jun '13**	Introduction	Minor text refinements
2.0	**13 Dec '13**	All	A major ontological realignment with the BIM Framework
		Concepts	An overhaul of concepts to match the BIM Framework
			Concepts are now referenced in singular tense
			Links to Knowledge Models are added
		Attributes	Replaced Relevance with Grade
			Replaced Number with Count
			Added Grade, Order and State
			Modified the description of all attributes – unified syntax
		Views	Merged Knowledge Matrix with Knowledge Document
			Calibrated the description of all Knowledge Views

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Gruber, T. R. (1995). Toward principles for the design of ontologies used for knowledge sharing? *International journal of human-computer studies, 43*(5-6), 907-928.

Milton, N. R. (2007a). *Knowledge Acquisition in Practice: A Step-by-step Guide*: Springer, London.

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Noy, N. F., & McGuinness, D. L. (2001). Ontology Development 101: A Guide to Creating Your First Ontology. http://www.lsi.upc.edu/~bejar/aia/aia-web/ontology101.pdf

Studer, R., Benjamins, V. R., & Fensel, D. (1998). Knowledge engineering: Principles and methods. *Data & Knowledge Engineering, 25*(1-2), 161-197.

Succar, B. (2009). Building information modelling framework: A research and delivery foundation for industry stakeholders. *Automation in Construction, 18*(3), 357-375.

Succar, B., Sher, W., & Aranda-Mena, G. (2007). *A Proposed Framework to Investigate Building Information Modelling Through Knowledge Elicitation and Visual Models*. Paper presented at the Australasian Universities Building Education (AUBEA2007), Melbourne, Australia. http://aubea.org.au/ocs/viewpaper.php?id=15&cf=1

APPENDIX B

The BIM knowledge content taxonomy

Appendix B: BIM knowledge content taxonomy v2.2

Building Information Modelling: conceptual constructs and performance improvement tools

Introduction

The BIM knowledge content (BKC) taxonomy includes multiple classifications to organize knowledge content within noteworthy BIM publications[1] (NBP)s and other knowledge deliverables. BIM knowledge content refers to conceptual and procedural knowledge[2] usable by an individual, team or organization to conduct a relevant activity or deliver a measureable outcome.

The taxonomy includes the following classifications:

- **BIM Knowledge Content Clusters** (BKCC) – three clusters and 18 labels, refer to section 1.1;
- **BIM Knowledge Content Relevance** (BKCR) – five relevance levels. refer to section 1.2;
- **BIM Knowledge Content Publication Type** (e.g. book, report, journal paper or web page);
- **BIM Knowledge Content Issuer Type** (e.g. government, commercial entity, industry association or community of practice);
- BIM Knowledge Content Geographical Coverage (e.g. Australia, US, UK or EU);
- **BIM Knowledge Content Format** (e.g. to-do list, flowchart, matrix or mind map); and
- **Other** classifications based on metrics (e.g. reliability, currency, interactivity and impact)

Below is an exploration of the two classifications used in papers B1 and B2:

[1] Noteworthy BIM publications (NBP)s refers to research by academia and efforts/initiatives by industry which cover BIM concepts and workflows, and result in one or more publications which are widely discussed, adopted or referenced.

[2] BCT applies to documents which include data/information intended for *human consumption and application*. BCT does not apply to data/information intended for *machine use or machine learning*. Software ontologies and metadata are two examples of what does not qualify for listing within/through the BCT.

BIM Knowledge Content Clusters

Th*e* BIM knowledge content clusters (BKCC) - the main classification within the BKC - is an extension of the three BIM fields (refer to paper A2), one of the three main components of the BIM framework. The BKCC includes numerous content labels (e.g. report, plan or programme) that can be used to assess the knowledge content of documents and other knowledge deliverables.

This classification has been used in paper B1 to assess noteworthy BIM publications (NBP)s and distribute them – not according to their titles but - according to their knowledge content. BKCC encourages an in-depth examination of NPBs' contents by "[shifting] the focus of perusal and interaction away from potentially uninformative document surrogates (such as titles, sentence fragments and URLs) to actual document content, and uses this content to drive the information seeking process" (White, Jose, & Ruthven, 2005 - page 1).

The BIM Content Taxonomy includes eighteen content labels[3] (Table 1) organized under three content clusters (Figure 1) – guides, protocols and mandates:

- **Guides**: documents which are *descriptive* <u>and</u> *optional*. Guides clarify goals, report on surveys/accomplishments or simplify complex topics. Guides do not provide detailed steps to follow to attain a goal or complete an activity.
- **Protocols**: documents which are *prescriptive* <u>and</u> *optional*. Protocols provide detailed steps or conditions to reach a goal or deliver a measureable outcome. While documents within this cluster are prescriptive, they are optional to follow unless dictated within a Mandate (see next cluster).
- **Mandates**: documents which are *prescriptive* <u>and</u> *dictated* by an authority. Mandates identify *what* should be delivered and – in some cases – *how, when* and *by whom* it should be delivered.

[3] BIM Content Labels are <u>not</u> mutually exclusive. A Noteworthy BIM Publication (NBP) may require three or more labels to adequately describe its contents.

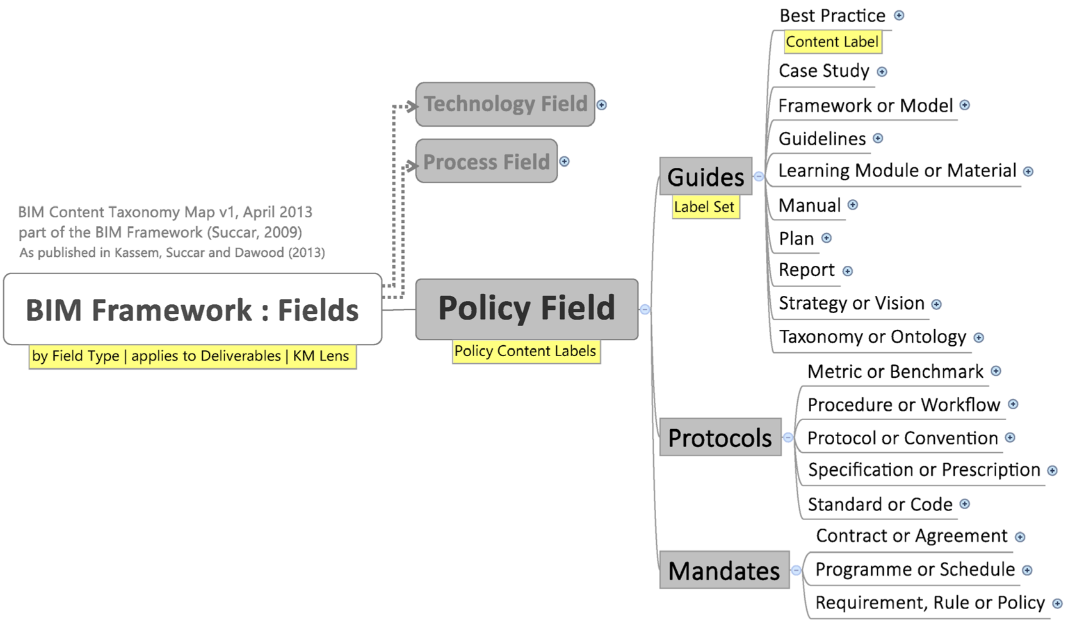

Figure 1. The BIM Content Taxonomy

Table 1. BIM Content Taxonomy

LABEL CLUSTER	**LABEL CODE**	**LABEL NAME**	**LABEL DEFINITION** - BIM SPECIFIC
Guides	G1	Best Practice	Operational methods arising from experience; promoted as advantageous; and replicable by other individuals, organizations and teams. This *label* applies to publications which list unambiguous and detailed recommendations, and which if applied as recommended, generate similar advantageous outcomes
	G2	Case Study	Summary and analysis (descriptive or explanatory) of projects and organizational efforts. This *label* applies to both research and industry publications which share lessons learned *by others,* and cover BIM deliverables, workflows, requirements, challenges and opportunities
	G3	Framework or Model	Theoretical structures explaining or simplifying complex aspects of the BIM domain by identifying meaningful concepts and their relationships
	G4	Guideline	Compilation of several BIM content types with the aim of providing guidance to individuals, teams or organizations. Guides typically provide insight into a complex topic (e.g. BIM Implementation Guide or Facility Handover Guide). Guides typically focus on knowledge-intensive topics, while Manuals (a complementary label) focus on skill-intensive ones. Due to the generic nature of this *label*, it should not be applied in isolation but in conjunction with other labels

LABEL CLUSTER	LABEL CODE	LABEL NAME	LABEL DEFINITION - BIM SPECIFIC
	G5	Learning Module or Material	All types of analogue and digital media (e.g. printed manual or online videos) which deliver conceptual or practical insight intended/suitable for education, training or professional development within industry or academia
	G6	Report	Compilation or summary of results arising from an assessment, calculation or review process (e.g. BIM capability report or profitability statement)
	G7	Strategy or Vision	Articulation of vision, mission and long-term goals. This *label* applies to publications which identify a long-term strategy (and possibly middle-term goals/milestones) but without identifying the resources required and detailed steps needed to fulfil the strategy
	G8	Taxonomy or Classification	Classification covering roles, types, levels, elements and other structured concepts. This *label* applies to publications which introduce classifications of five or more items within a structured list; and which have a clear use in assessment, learning or implementation (e.g. construction elements, BIM roles, data exchange types or levels of detail)
Protocols	P1	Metric or Benchmark	Tools and criteria suitable for establishing levels of performance of systems, projects, individuals, teams, organizations and other organizational units[4]. This *label* applies to publications which include tools or explicit metrics/indicators for establishing usability, profitability, productivity, competency, capability or similar
	P2	Manual	A structured document which is intended to clarify the steps needed to perform a measureable activity or deliver a measureable outcome (e.g. BIM training Manual). Manuals typically focus on skill-intensive topics, while Guides (a complementary label) typically focus on skill-intensive ones. Due to the generic nature of this *label*, it should <u>not be applied in isolation</u> but in conjunction with other labels
	P3	Plan	A document describing activities to be performed, resources to be used and milestones to be reached within a defined timeframe. This *label* applies to publications describing – in adequate detail - how a specific strategy can be fulfilled or a pre-defined goal can be reached (e.g. a BIM Implementation Plan detailing how to fulfil a BIM Capability Strategy)
	P4	Procedure or workflow	Structured information covering successive steps needed to fulfil an operational, rather than strategic, requirement. A documented Procedure includes the small steps needed to deliver, if executed by a competent individual, a pre-defined and desired

[4] There are 12 organizational units, each with their own unique metrics (refer to Building Information Modelling Maturity Matrix (Succar, 2010).

LABEL CLUSTER	**LABEL CODE**	**LABEL NAME**	**LABEL DEFINITION** - BIM SPECIFIC
			outcome. A Workflow identifies major successive activities to be performed and decision gates to pass-through towards reaching a delivery milestone or fulfilling a project/organizational objective
	P5	Protocol or Convention	Agreed or customary method of product/service development or delivery which are not *by themselves* contractually binding (e.g. keeping minutes of meetings, how to name files and frequency of exchanging models)
	P6	Specification or Prescription	A set of criteria used to define or judge the quality of products (e.g. object dimensions or data richness) and services (e.g. timeliness). Specifications may or may not be a Standard (a separate label). COBie is an example of BIM-related specifications which may become a service/delivery standard over time
	P7	Standard or Code	Detailed set of product/service descriptions (prescriptive or performance-based) acting as a reference to be measured against. This label typically denotes a set of specifications (a separate label) which are authoritative and test-proven (e.g. barrier-free or accessibility standards)
Mandates	M1	Contract or Agreement	Legally-binding document and its subparts – including contractual additions, amendments and disclaimers. This *label* applies to contracts and clauses, not to publications describing or promoting them (e.g. the label applies to AIA Documents E203, G201 and G202 but not to the AIA IPD guide)
	M2	Programme or Schedule	A document associating one or more classification to time and/or location. For example, a BIM competency improvement programme is a document linking BIM competencies, BIM roles (and possibly other classifications) to a timeline or target dates
	M3	Requiremen t, Rule or Policy	Expectation or qualification mandated by clients, regulatory authorities or similar parties. This *label* applies to publications with explicit identification of requirements to be met (e.g. organizational capability or previous experience) or products/services to be delivered (e.g. a tender/bid document)

BIM Knowledge Content Relevance

The BIM knowledge content relevance (BKCR) is a classification that can be applied to the knowledge deliverables (e.g. documents or publications) of organizational units. The BKCR includes five *relevance values* (R-values):

- **R0 - Redundant:** the deliverable is dated or includes information which is no longer useful
- **R1 - Relevant**: the deliverable is relevant, current and contains actionable information
- **R2 - Regarded:** the deliverable is highly-relevant, well-cited and well-used
- **R3 - Recommended:** the deliverable is authoritative and impactful and considered a reference
- **R4 - Requisite:** the deliverable is the most authoritative in its relevant domain

The BKCR classification has been used in paper B2 to assess noteworthy BIM publications and test their contribution towards country-scale maturity.

Notes

As discussed in Paper B2 (Kassem, Succar, & Dawood, 2014), the BKC taxonomy provides – in addition to organizing knowledge within NBPs - the traditional functions of *indexing support* and *retrieval support* (Hedden, 2010). The BKC facilitates indexing support through its controlled vocabulary which allows *indexers* to classify documents in a consistent manner. Without a controlled vocabulary, multiple documents with the same content may erroneously carry different headings. Indexers may also inadvertently use synonyms for classifying similar documents (Hedden, 2010, p. 15).

Retrieval support is a direct consequence of indexing support (Hedden, 2010, p. 22) and refers to the ability of a classification to facilitate searching and improve find-ability within databases. The BKC taxonomy can be readily transformed into a facetted classification with its labels (a content type *facet*) augmented with additional facets – e.g. a content format facet, content relevance facet or issuer type facet. The BKC can thus support both information retrieval and the faceted analysis (Kwasnik, 1999).

Version history

The Revision Table below lists previous iterations and their change log:

V.	Date	Applies to	Description
1.0	**2 Aug '11**	All	Initial version
1.1	**21 Jan '12**	Labels	Content labels renamed
1.2	**10 Jan '13**	Definitions	Minor changes to Summary Definitions
1.3	**11 Feb '13**	Introduction	Text modified to enhance clarity of purpose
		Labels	Label syntax changed from plural to singular
1.4	**16 Feb '13**	Labels	New more granular labels added
			Hybrid labels introduced
		Classifications	Renamed 'Other Classifications' to 'Complementary Classifications'
1.5	**11 Apr '13**	Introduction	Added quote
			Included 2 images to explain how the taxonomy development
		Labels	Added three Content Label Sets
			Removed 'Assessment Tool' to avoid overlap with Metrics
1.6	**29 May '13**	Title	Renamed from BIM Content Taxonomy (BCT) to BIM Knowledge Content (BKC) taxonomy to clarify the use of the BIM Management Lens in generating all classifications
		Classifications	Added the 'Relevance' classification to be used in a CIB W78 conference paper (Kassem, Succar and Dawood, 2013)
		Labels	Modified labels to match updated naming of BIM fields
2.0	**8 Jun '13**	Introduction	Updated for submission as an appendix to the PhD thesis
		Classifications	Reorganized all classifications
			Provided text to discuss two main classifications (BKCC and BKCR) and identified where they have been used
			Removed 'Authority' as a separate classification type to avoid overlaps with the 'Mandates' cluster within BKCC
2.1	**18 Jun '13**	Introduction	Minor text refinements
2.2	**19 Sep '13**	New section	Added a Notes section

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APPENDIX C

Citations of published papers

Appendix C: citations of published papers v1.0

Building Information Modelling: conceptual constructs and performance improvement tools,

This appendix is a compilation of citations received for published papers submitted as part of this study. Starting in 2008, citations were monitored[1] and recorded to provide insights into *what* and *how* published papers, conceptual constructs and practicable tools have been received by domain researchers. These citations contribute to the thesis' validity argument and will hopefully encourage other research students to adopt a *thesis by publication* strategy. This compilation will be become outdated rapidly. However, it will serve as a benchmark to compare future citation numbers and citation contents over a number of years. It will thus facilitate the analysis of the study's research impact, clarify if/which/how BIM framework components have been adopted, and inform the development of new conceptual structures.

Table 1 provides a summary of citations received by *type A papers*[2], peer-reviewed articles with the PhD candidate being the sole or primary author. Table 2 is a non-exhaustive list of citing articles with a succinct analysis of *how* this study's concepts and tools were cited:

Table 1. A summary of published papers and their total citations to date.

Code	Paper title	Reference	Article Type	Publication Year	Citations to date
A1	A Proposed Framework to Investigate Building Information Modelling Through Knowledge Elicitation and Visual Models	(Succar, Sher, & Aranda-Mena, 2007)	Conference paper	2007	6
A2	Building information modelling framework: A research and delivery foundation for industry stakeholders	(Succar, 2009)	Journal paper	2009	192
A3	Building Information Modelling Maturity Matrix	(Succar, 2010a)	Book chapter	2010	19
A4	The Five Components of BIM Performance Measurement	(Succar, 2010b)	Conference paper	2010	19
A5	Measuring BIM performance: Five metrics	(Succar, Sher, & Williams, 2012)	Journal paper	2012	3
A6	An integrated approach to BIM competency assessment, acquisition and application	(Succar, Sher, & Williams, 2013)	Journal paper	2013	n/a
				Total citations received by official submission date - June 30, 2013:	**176**
				Total citations received by final thesis submission - December 14, 2013:	**239**

[1] Citations of published works were mainly monitored using automatic citation alerts sent by SCOPUS and Google Scholar. Some published works – which are not indexed by search engines - where discovered during literature reviews conducted throughout this study.
[2] Paper types B and C are excluded from this appendix. For more information about paper types, please refer to section 9 of Part I.

Table 2. A succinct review of citing articles including the context in which the citation is provided

	Publication title	Type/Date	Context	Reference
Paper A1: A Proposed Framework to Investigate…				
1	Building Surveying: A Sustainable Profession or A Passing Fad?	Conference Paper March 2008	"In fact if we are to believe some of the claims that are being made by the developers of the new Building Information Modelling (BIM) systems it will not be long before we have a tool that allows for digital documentation, digital take offs and measurement linked to a pricing and costing program with a digital link to the BCA which will enable the architects' original digital documentation to be measured, costed and checked against the provisions of the BCA at the touch of a button or the click of a computer mouse (Succar et al 2007)." p. 98	(Zillante, 2008)
2	Building information modelling demystified: does it make business sense to adopt BIM?	Journal Paper March 2009	Succar et al. (2007) defined BIM as "a set of interacting policies, processes and technologies producing a methodology to manage the essential building design and project data in digital format throughout the building's life-cycle" – p. 421	(Aranda-Mena, Crawford, Chevez, & Froese, 2009)
3	Towards Integrated Design and Delivery Solutions: Pinpointed Challenges of Process Change	Journal Paper November 2010	"The term building information modelling is considered to include the process of exchanging information and working on the BIM(s) (Succar et al., 2007)" p. 264	(Rekola, Kojima, & Mäkeläinen, 2010)
4	An Ethnographically Informed Analysis of Design Intent Communication in BIM-enabled Architectural Practice	PhD Thesis October 2011	"Succar et al. (2007) argued for the emerging and revolutionary role of BIM in practice, as it produces a technological and procedural shift that affects all participants in the AEC industry. They also highlight the interaction between processes, technologies and policies that takes place in BIM to generate a consistent methodology that manages design and project information throughout a building lifecycle. At the same time, they point out the issues related to semantics, meaning and interpretation that result from the engagement of multiple participants in the process" p. 14	(Abdelmohsen, 2011)
5	Building Information Modelling (BIM),	Conference Paper	Generic Citation (also references a white paper by ChangeAgents)	(Patrick, Munir, &

	Publication title	Type/Date	Context	Reference
	Utilised During the Design and Construction Phase of a Project has the Potential to Create a Valuable Asset in its Own Right ('BIMASSET') at Handover that in turn Enhances the Value of The Development	October 2012		Jeffrey, 2012)
6	Architectural Technology and the BIM acronym: Critical Perspectives of Evangelical and Evolutionary Paradigms for Technical Design	Conference Paper March 2013	Model used without citation. The BIM Nodes model, as used with permission and attribution by Mr Sohail Razvi in an AECbytes blogpost, is not referred back to the model's author. "In a BIM business model, Razvi (2008) noted that a third technology node which interlocks with the other two has become critical to process development (Fig. 1)" – page 124	(Kouider & Paterson, 2013)
	Paper A2: Building information modelling framework…			
1	Building Information Modelling (BIM) System in Construction in 2020: Opportunities and Implications	Conference Paper January 2009	"Several efforts have been made by some authors to provide comprehensive definitions of BIM"…"Guillermo Aranda-Mena, John Crawford et al. (2008) and (Succar 2008) provide holistic description of the trend of BIM adoption and implementation in different parts of the world"… "However, efforts are on-going by application developers, researchers and policy makers to improve the slow of BIM adoption and further define business factors that are inherent in BIM deployment" – pp. 2 & 5	(Olatunji & Sher, 2009)
2	Information management in industrial housing design and manufacture	Online Journal June 2009	"Hence, according to Succar (2009), BIM can be regarded as a methodology to manage product data throughout a building's life-cycle consisting of a set of interacting policies, processes and technologies." – p. 112	(Persson, Malmgren, & Johnsson, 2009)
3	Empirical Analysis of Construction Enterprise Information Systems: Assessing the Critical Factors and Benefits	PhD Thesis 02.07.09 (available online)	"Many powerful software systems are being utilized during the project life cycle in the construction environment. Yet, since insufficient attention has been given to the integration of these systems, an islands of automation' problem has emerged. System integration, which	(Tatari, 2009)

Publication title		Type/Date	Context	Reference
			enhances "the value added in whole network of shareholders throughout the building lifecycle" (Succar 2009), is necessary to avoid this problem" p. 39	
4	Model for developing trust in construction management	PhD Thesis August 2009	"Currently, BIM is characterized as a tool, process and/or product that develops virtual intelligent models linked to other construction management tools (i.e. schedule, estimates) that promote collaboration, visualization and constructability reviews beneficial to all stakeholders throughout the lifecycle of the facility (Kymmell 2008; Succar 2009)" p. 117	(Zuppa, 2009)
5	Developing a multidisciplinary process view on IFC standardization	Conference Paper September 2009	Minor misquote	(Laakso, 2009)
6	Services in Digital Design: new visions for AEC-field collaboration	Journal Paper Sep 2009	"Succar's extensive BIM definition attempts to form a unified description of contemporary BIM [16] (p. 465)... connecting also a global socio-political issue of modelling for long term building design [16] (p. 468)... Policy issues are crucially important in the preliminary phases of a building project planning, i.e. before the project launch. This was well addressed in the pre-interviews performed in the early of this research study. Also Succar claims decision making and policy being one constitutive field for building information models [16] - p. 472.	(Penttila, 2009)
7	Simulation and BIM For Building Design, Commissioning and Operation: a Comparison with The Microelectronics Industry	Conference Paper 23.09.09 (available online)	"Recent developments in the buildings industry and the associated legislation are moving towards a more automated and integrated approach. The recognition of building simulation in recent legislation leading to more widespread adoption as well as the ongoing development and increasing adoption of the Building Information Management (BIM) methodology (including adoption by the US Army (Succor, 2009)) are steps in this direction." – p. 1539	(Tuohy, 2009)
8	A Study of the Deployment and Impact	Conference Paper	"Interoperability – Succar (2009 p.363) defines interoperability as	(Davidson, 2009)

	Publication title	Type/Date	Context	Reference
	of Building Information Modelling Software in the Construction Industry	Oct 2009	'the ability of two or more systems or components to exchange information and to use the information that has been exchanged" – p. 4	
9	Automated construction schedule creation using project information model	Conference Paper Oct 2009	One citation "Information which is contained in BIM is usually aggregated. If we need specific information, we have to select it and conceptually divide it based on fields and stages and also through the point of view, which is called through lens. Depending on how much information is included in BIM, fields and stages can be sub-divided according to the meaning of the information (Succar B. 2009)."	(Mrkela & Rebolj, 2009)
10	Modelling sustainable and optimal solutions for building services integration in early architectural design: confronting the software and professional interoperability deficit	Conference paper Nov, 2009	More consideration is being given to whole of building lifecycle considerations earlier on in the design process, which is necessitating the embrace of integrated design policies, technologies and processes (Succar, 2009)	(Toth, Fernando, Salim, Drogemuller, Burry, Burry, & Frazer, 2009)
11	New Interfaces, new scenarios. Vroom n.0: Vroom n.0: The emerging potential of collaborative 3D web platforms	Conference Paper Nov 2009	No quote…referencing Succara	(León & Molina, 2009)
12	Research and development of high-rise steel structural BIM software and its application in Shanghai Center Project	Journal Paper (Chinese Language) Nov 2009	No longer available online	(Ji, Zhang, Yang, & Chang, 2009)
13	A CAD-Based Interface Management System using Building Information Modelling in Construction	Book Chapter Jan 2010	Generic citation	(Lin, 2010)
14	Building Information Modelling in the Australian Architecture, Engineering and Construction Industry	Book Chapter Jan 2010	"Succar (2009) proposed a BIM framework which aims to provide a research and delivery foundation so that industry practitioners can have a better understanding of underlying knowledge structures and from this are able to negotiate implementation requirements. This is a tri-axial model involving BIM stages, BIM lenses and BIM fields.	(Gerrard, Zuo, Zillante, & Skitmore, 2010)

Publication title		Type/Date	Context	Reference
			The model also defined the interactions between policy, technology and process is imperative for the implementation of BIM in the AEC industry." p. 524	
15	Effective Capture, Translating and Delivering Client Requirements Using Building Information Modelling (BIM) Technology	Conference paper Jan 2010	Referenced in bibliography only	(Shahrin, Johansen, Lockley, & Udeaja, 2010)
16	The application of Building Information Modelling in Facilities Management	Book Chapter Jan 2010	Generic citation	(Olatunji & Sher, 2010b)
17	Understanding adoption and use of BIM as the creation of actor networks	Journal Paper Jan 2010	"…the actor network approach can also be applied on the framework developed by Succar [45] in which three interrelated and reinforcing fields (each of them encompassing a wide array of actors) are identified in order to frame BIM implementation." p. 71	(Linderoth, 2010)
18	Value proposition of interoperability on BIM and collaborative working environments	Journal Paper Jan 2010	"Hence, it becomes necessary to understand the value level that BIM and interoperability may bring to AEC players [47]" references Succur [sic] - p. 527	(Grilo & Jardim-Goncalves, 2010)
19	Effective Capture, Translating and Delivering Client Requirements Using Building Information Modelling (BIM) Technology	Workshop Paper Feb 2010	Referenced in bibliography but not cited within text	(Shahrin et al., 2010)
20	Meer begrip voor meer grip - Greater understanding of grip-graduate research into the use of virtual construction by construction companies in the B & E sector to obtain quantities	Master's Thesis Feb 2010	Extensive quotes	(Idema, 2010)
21	Fostering E-Services in Architecture and Construction Using the Building Information Model	Conference Paper March 2010	Extensive citations and use of knowledge models	(Reffat, 2010)
22	Advantages And Disadvantages of Vertical Integration in	Master's Thesis May 2010	Multiple quotes and one visual knowledge model (modified)	(Lehtinen, 2010)

Publication title		Type/Date	Context	Reference
	The Implementation of Systemic Process Innovations: Case studies on implementing building information modelling (BIM) in the Finnish construction industry			
23	Building Information Modelling Processes: Benefits for Construction Industry	Conference Paper May 2010	Many generic references plus one inaccurate statement: "According to (Succar 2009), it is difficult to effect, monitor and manage change in the construction industry."	(Olatunji, Sher, Gu, & Ogunsemi, 2010)
24	Building Information Modelling: Literature Review on Model to Determine the Level of Uptake by Organisation	Conference Paper May 2010	The ICMM limitation (a full page) plus two images are copied/referenced from the BIM Maturity Matrix Chapter.	(Haron, Marshall-Ponting, & Aouad, 2010)
25	Implementation of Building Information Modeling in Architectural Firms in India	Master's of Science, Purdue May, 2010	No quote, just listed in the bibliographic section	(Luthra, 2010)
26	A review and outlook for a 'Building Information Model' (BIM): A multi-standpoint framework for technological development	Journal Paper June, 2010	Extensive quotes and a Figure (the BIM Cube) influenced by some of the framework's visual models.	(Cerovsek, 2011)
27	Developing incentives for collaboration in the AEC Industry	Conference Paper June 2010	A couple of citations plus using the BIM Fields venn diagram (Figure 1, page 2	(Oti & Tizani, 2010)
28	Research and application of Building Information Modelling (BIM) in the Architecture, Engineering and Construction (AEC) industry: a review and direction for future research	Conference Paper June 2010	Inaccurate citation "Current delivery methods include providing the facility manger with CAD documentation or creating a *Record BIM* (Succar 2009) but this is highly inadequate." p. 7	(Wong & Yang, 2010)
29	BIM - A Driver for Change	Conference Paper June-July 2010	"Succar defines a series of (increasingly integrated) stages in the deployment of BIM and notes that the associated changes at an organisational and industrial level will be transformational rather than incremental (Succar, 2009)"…. "Just how this will resolve itself is unclear but, as Succar implies, some form of IT based integrated project	(Watson, 2010)

Publication title		Type/Date	Context	Reference
			delivery will be part of the solution." p. 6	
30	Exploring the challenges for the implementation and adoption of BIM	Master's Thesis July, 2010	Extensive quotes	(Younas, 2010)
31	Closure to "Areas of Application for 3D and 4D Models on Construction Projects"	Journal Paper August, 2010	Mistakenly refers to the framework as advocating a single integrated model: "In particular, our experience with applying BIM in practice does not support the notion—put forth by the discusser and others, e.g., Succar (2009)—that one integrated information model of a building can technically support all practical data needs throughout the life cycle of a project" – p. 933	(Hartmann, Gao, & Fischer, 2010)
32	Assessing the Impact of New Rules of Cost Planning on Building Information Model (BIM) Schema Pertinent to Quantity Surveying Practice	Conference Paper Sep 2010	Multiple citation and an adaptation of the BIM Fields Venn diagram	(Matipa, Cunningham, & Naik, 2010)
33	Application of Building Information Model (BIM) in building thermal comfort and energy consumption analysis	Master's Thesis Oct 2010	A few quotations	(Yiye, 2010)
34	Enhancing Control of Built Assets through Computer Aided Design - Past, Present and Emerging Trends	Conference Paper Oct 2010	Multiple quotes, two diagrams and one table have been adapted.	(Oommen, 2010)
35	KPIs: Analyzing the impact of Building Information Modeling on construction industry in China	Conference Paper October 2010	Mistaken attribution to Fig.1 - a visual knowledge model by Alan Edgar	(Wei-zhuo & Guo-qiang, 2010)
36	Model Interoperability in Building Information Modelling	Journal Paper October 2010	"Building Information Modelling is an interdependent network of policies, processes and technologies [3]…" p. 2	(Steel, Drogemuller, & Toth, 2010)
37	Attributes of Building Information Modelling Implementations in Various Countries	Journal Paper November 2010	Extensive Use. The three BIM Fields are used to structure the whole paper.	(Wong, Wong, & Nadeem, 2010)
38	BIM-based Scheduling of Construction: A Comparative Analysis of Prevailing and BIM-	Conference Paper November 2010	"There are numerous explanations and definitions of Building Information Modeling, BIM, available in literature, e.g. … *a set*	(Andersson & Büchmann-Slorup,

	Publication title	Type/Date	Context	Reference
	based Scheduling Processes		*of interacting policies, processes and technologies… (Succar 2009)…"* p. 3	2010)
39	Building Information Modeling in Local Construction Industry	Master Thesis December 2010	A few general citations	(Baba, 2010)
40	Government roles in implementing building information modelling systems: Comparison between Hong Kong and the United States	Journal Paper December 2010	Cursory note as a general resource	(Wong, Wong, & Nadeem, 2011)
41	'Using the Knowledge Transfer Partnership model as a method of transferring BIM and Lean process related knowledge between academia and industry: A Case Study Approach	Conference Paper December 2010	"The development of curricula and learning material very much depends on a prediction of the future. Using the BIM maturity index maybe one way of considering future development (Succar, 2009)." p. 6	(Coates, Arayici, & Koskela, 2010)
42	BIM - the Next Step in the Construction of Civil Structures	Master's Thesis 2010	Multiple use of definitions and visual knowledge models	(Winberg & Dahlqvist, 2010)
43	Building information modelling (BIM) framework for practical implementation	Journal Paper 2010	"A more comprehensive BIM perspective was recently proposed by Succar [40], encompassing far more variables than those identified in CIC frameworks" – p. 127	(Jung & Joo, 2010)
44	Building Information Modeling and Quantity Surveying Practice	Journal Paper 2010	Use of a Knowledge Model, "Some common interpretations of BIM" – Figure 2, p. 69	(Olatunji, Sher, & Gu, 2010a)
45	Industrialised Housing Design Efficiency	Master Thesis 2010	Several citations specifically related to BIM stages. One figure (BIM Stages – linear model) used	(Jansson, 2010)
46	Implementation of Building Information Modeling (BIM) in Construction: A Comparative Case Study	Conference Paper 2010 (possibly submitted Dec o9)	Generic citation	(Rowlinson, Collins, Tuuli, & Jia, 2010)
47	Modelling Outcomes of Collaboration in Building Information Modelling Through Gaming Theory Lenses	Book Chapter 2010	General references within the article	(Olatunji, Sher, & Gu, 2010b)
48	Legal Implications of BIM: Model Ownership and Other Matters Arising	Conference Paper 2010	"To address this (Succar 2009) suggests that BIM adoption and implementation frameworks must be comprehensive and objective, involving all stakeholders – the industry, government and	(Olatunji & Sher, 2010a)

	Publication title	Type/Date	Context	Reference
			research" – p. 460	
49	Optimizing BIM Adoption and Mindset Change - Emphasize on a Construction Company	Master's Thesis 2010	Adaptation of the BIM Stages – reference not included in bibliography list although it is mentioned within the body of the thesis	(Mulenga & Han, 2010)
50	The Impact of Building Information Modelling on Construction Cost Estimation	Conference Paper 2010	"According to (Succar 2009), the applications of BIM transcend discipline or institutional boundaries, and its definitions are being tailored to multidisciplinary concepts" – p. 195	(Olatunji, Sher, & Ogunsemi, 2010)
51	Using BIM as a Project Management Tool - How can BIM improve the delivery of Complex Construction Projects?	Master's Thesis January 2011	Multiple citations and images	(Broquetas, 2011)
52	Design Error Reduction: Toward the Effective Utilization of Building Information Modeling	Journal paper March 2011	Multiple generic references. The BIM definition developed through the framework is mistakenly attributed to Penttila	(Love, Edwards, Han, & Goh, 2011)
53	A review and outlook for a 'Building Information Model' (BIM): A multi-standpoint framework for technological development	Journal Paper April 2011	Multiple citations and an acknowledgement of assistance	(Tomo, 2011)
54	Analysis of the Information Needs for Existing Buildings for Integration in Modern BIM-Based Building Information Management	Conference Paper May 2011	Multiple citations and the use of the Venn Diagram image (BIM Fields)	(Godager, 2011)
55	A Preliminary Review on the Legal Implications of BIM and Model Ownership	Journal Paper May 2011	"To address this (Succar, 2009) suggests that BIM adoption and implementation frameworks must be comprehensive and objective, involving all stakeholders – the industry, government and research" p. 693	(Olatunji, 2011b)
56	Knowledge and Technology Transfer from Universities to Industries: A Case Study Approach from the Built Environment Field	Conference Paper May 2011	One quote: "BIM can provide the required valued judgments that create more sustainable infrastructures, which satisfy their owners and occupants (Succar, 2009)" p. 6	(Arayici, Coates, Koskela, & Kagioglou, 2011)
57	Modelling Organizations' Structural Adjustment to BIM Adoption: a Pilot Study	Journal Paper May 2011	Inaccurate citation: "This research was conducted in Australia. Some authors have reported that BIM adoption in Australia is still slow	(Olatunji, 2011a)

	Publication title	Type/Date	Context	Reference
	on Estimating Organizations		(e.g. (London et al., 2008, Succar, 2009))" p. 660	
58	The 3D Coordinated Building Design Based on Building Information Modeling	Journal Paper May, 2011	A couple of quotations plus a use of one image "Building Information Models and their objects — flow diagram" p. 6588, Fig. 1	(Lv, Zou, Huang, & Xu, 2011)
59	BIM facilitated web service for LEED automation	Conference Paper June 2011	Several citations…The authors adapted the BIM Stages model to a BIM-LEED process integration road map.	(Wu, 2011)
60	Research Project Cost Benefits of Integrated Planning: First experiment-results	Journal paper June 2011	"Building Information Modelling (BIM) is a set of interacting policies, processes and technologies generating a "methodology to manage the essential building design and project data in digital format throughout the building's life-cycle" (Succar, 2009)." p. 258	(Kovacic, Filzmoser, Faatz, & Koeszegi, 2011)
61	The BIM-Based Information Integration Sphere for Construction Projects	Conference Paper June 29, 2011	"Although many researchers and organizations have developed guidelines and frameworks for BIM adoption into the AEC industry [1,2], outlining the added value benefit of BIM to the industry as a whole (and not as a desperate set of technologies), and even though these researches have contributed to this field of study, they still lack in developing an information model to effectively map different BIM processes and stakeholders, and integrate the information resulting from the various data exchanges and interaction between them." p. 156	(Feng, Mustaklem, & Chen, 2011)
62	Enhancing Maintenance Management Using Building Information Modeling In Facilities Management	Conference Paper June-July 2011	One citation: "Succar (2009) explored publicly available international guidelines and introduced the BIM framework, a research and delivery foundation for industry stakeholders" pp. 753-4	(Su, Lee, & Lin, 2011)
63	Creation of an Evolutive Conceptual Know-how Framework for Integrative Building Design	Conference Paper July 2011	Generic citation	(Iordanova, Forgues, & Chiocchio, 2011)
64	How to Measure the Benefits of BIM, a Case Study Approach	Master's Thesis August 2011	Multiple citations	(Barlish, 2011)
65	Empirical Analysis of Construction Enterprise Information Systems: Assessing System	Journal Paper September 2011	One citation: "System integration, which enhances "the value added in whole network of shareholders throughout the building lifecycle"	(Tatari & Skibniewski, 2011)

Publication title		Type/Date	Context	Reference
	Integration, Critical Factors, and Benefits		(Succar 2009), is necessary to avoid this problem”.	
66	Integrating BIM and Planning Software for Health and Safety Site Induction	Conference Paper September 2011	“Succar (2009) gave a deeper description for BIM as he defined it as a set of interacting polices, process and technologies generating a methodology to manage the key building design information in a digital format throughout the building life-cycle”.	(John & Ganah, 2011)
67	Digital Buildings - Challenges and Opportunities	Journal Paper October, 2011	“Succar defines a series of (increasingly integrated) stages in the deployment of BIM and notes that the associated changes at an organisational and industrial level will be transformational rather than incremental.”	(Watson, 2011)
68	A Framework for Building Information Fusion	Conference Paper October 2011	Minor citation	(Bogen, Rashid, & East, 2011)
69	Beyond MOF Constraints - Multiple Constraint Set Meta modelling for Lifecycle Management	Conference Paper October 2011	One citation	(Duddy & Kiegeland, 2011)
70	*BIM Versus PLM: Risks and Benefits*	Conference Paper October 2011	BIM is “the process of creating and using digital models for design, construction and/or operations of projects” according to [Succar, 2009],	(Otter, Pels, & Iliescu, 2011)
71	CloudBIM: Management of BIM Data in a Cloud Computing Environment	Conference Paper October 2011	“A building information model at the very simplest level can be viewed as the complete collection of information about a building, offering a phaseless workflow (Succar 2009)”. BIM data is accessed and manipulated by utilising certain “tools of enquiry”, such as “lenses” and “filters”; lenses highlight certain objects that meet a particular criteria (e.g. photovoltaic) whilst filters remove objects that do not meet the criteria (Succar 2009)”.	(Bogen et al., 2011)
72	A Domain Specific Software Model for Interior Architectural Education and Practice	Journal Paper November 2011	Attribution (citation only loosely refers to what is wrote within the BIM Framework): “The general-purpose software are chosen due to their wide spread use and long existence in the market, as well as their varied utilization in 2D drawing, 3D	(Şenyapılı & Bozdağ, 2012)

Publication title		Type/Date	Context	Reference
			modeling and building information modeling (BIM) [4,19]."	
73	On Decision-Making and Technology-Implementing Factors for BIM Adoption	Conference Paper Nov 2011	Multiple citations of 2 papers	(Mom, Tsai, & Hsieh, 2011)
74	BIM Adoption in Iceland and Its Relation to Lean Construction	Master's Thesis December 2011	Extended citation of BIM Stages plus the usage of three images: BIM as MIB, Project Lifecycle Phases liner model and BIM Maturity Stage.	(Kjartansdóttir, 2011)
75	Validation of Autodesk Ecotect™ Accuracy for Thermal And Daylighting Simulations	Conference paper December 2011	General reference only – no citation	(Vangimalla, Olbina, Issa, & Hinze, 2011)
76	Process-and project-level issues of design management in the built environment	Doctoral Thesis	"Succar (2009) defined BIM as an integrated concept consisting processes, policies and technology" p. 69 (disagrees with the definition)	(Zerjav, 2012)
77	Building Information Modeling and Integrated Project Delivery in the Commercial Construction Industry: A Conceptual Study	Journal Paper January 2012	"In response to the increase in BIM-related research, Succar (2009) developed a research framework to: systematize knowledge; advance awareness and implementation; recast BIM as an integrated solution; and connect the gap that exists between the understandings of BIM by those in academia and their counterparts in active practice (p. 358). Refer to Fig. 2 for a depiction of Succar's (2009) framework, which represents the interplay of BIM fields (players and deliverables), stages (implementation maturity) and lenses ("knowledge views"). Succar (2009) argues that IPD should be the desired endpoint of all BIM implementations, concurring with the AIA (2007) and Froese's (2010) analysis, stating that, "…the long term vision of BIM [is that of] an amalgamation of domain technologies, processes and policies" P. 25 Tri-axial Framework image reused	(Ilozor & Kelly, 2012)
78	Building Information Modeling Integrated with Electronic Commerce Material Procurement and Supplier Performance	Master's Thesis February 2012	Two figures and extensive citations covering BIM Fields, Capability and Maturity	(Ren, 2011)

	Publication title	Type/Date	Context	Reference
	Management System			
79	Expanding uses of building information modeling in life-cycle construction projects	Journal Paper February 2012	Two citations: "BIM is connected usually to more integrated collaborative processes also when it comes to contractual relationships (in a mature form realized in "Integrated Project Delivery")" "A most "mature" use of BIM is seen to involve collaboratively created, shared, and maintained models across project lifecycle [11]."	(Hannele, Reijo, Tarja, Sami, Jenni, & Teija, 2012)
80	Using building information modeling to assess the initial embodied energy of a building	Journal Paper February 2012	"[BIM] is an emerging technological and procedural shift within the Architect [sic], Engineering, Construction (AEC) and Operations industry (Succar, 2009)." p. 4	(Shrivasta & Chini, 2012)
81	Epistemology of Construction Informatics	Journal Paper March 2012	"…life cycle and temporal contexts, the evolving nature of data and their use with time, is becoming an integral part in any recent BIM strategy (see for example…Succar 2009…)	(El-Diraby, 2012)
82	How to measure the benefits of BIM — A case study approach	Journal Paper (based on Master's Thesis referenced above March 2012	General citation	(Barlish & Sullivan, 2012)
83	Building Information Modeling: Trends in the US Construction Industry	Journal Paper April 2012	General citation	(Sattineni & Bradford, 2012)
84	User-centric knowledge representations based on ontology for AEC design collaboration	Journal Paper April 2012 (online)	General citation	(Lee & Jeong, 2012)
85	User perceptions of ICT impacts in Swedish construction companies: 'it's fine, just as it is'	Journal Paper April 2012	General citation	(Jacobsson & Linderoth, 2012)
86	Why advanced buildings don't work?	Conference Paper April 2012	Two citations "The BIM initiative may provide a framework within which improved processes could be integrated (Succar, 2009)"" Processes to address the performance gaps identified here do not yet appear to be defined or even a focus within the current BIM roadmap (Succar, 2009, BIS, 2012).	(Tuohy & Murphy, 2012)

	Publication title	Type/Date	Context	Reference
87	A Framework for an Integrated and Evolutionary Body of Knowledge	Conference Paper May 2012	“The level of maturity as to the adoption of new methods of work and new technologies can be measured through a maturity matrix. Succar (Succar, 2008) recently proposed a framework for BIM, including process, technology and policy aspects. On this same basis, he also developed a maturity matrix for BIM adoption.”	(Forgues, Iordanova, & Chiocchio, 2012)
88	Generic Model for Measuring Benefits of BIM as a Learning Tool in Construction Tasks	Journal Paper May 2012	One citation ‘Building information modeling is argued to be a useful tool for reducing the construction industry’s fragmentation, improving its efficiency/effectiveness, and lowering the high costs of inadequate interoperability (Succar 2009)’’	(Lu, Peng, Shen, & Li, 2013)
89	Toward Performance Assessment of BIM Technology Implementation	Conference Paper June 2012	Extensive referencing of three articles: The BIM Framework, The BIM Maturity Matrix and The Five Components of BIM Performance Measurement (most citations are from the BIM Maturity Matrix)	(Mom & Hsieh, 2012b)
90	Toward performance assessment of BIM technology implementation	Conference Paper Jun 2012	Multiple citations of 3 papers	(Mom & Hsieh, 2012a)
91	Authorization Framework using Building Information Models	Journal Paper July 2012	General Citation	(Skandhakumar, Reid, Dawson, Drogemuller, & Salim, 2012)
92	A Knowledge-Based Framework for Automated Space-Use Analysis	Technical Report July 2012	General citation	(Kim, Rajagopal, Fischer, & Kam, 2012)
93	BREEAM Based Dynamic Sustainable Building Design Assessment	Conference Paper July 2012	One citation “Building information modelling is becoming an indispensable tool for providing integrated solutions to the current AEC (Succar 2009)”.	(Kasim, LI, & Rezgui, 2012)
94	Mobile 2D Barcode/BIM-based Facilities Maintaining Management System	Conference Paper July 2012	“Succar (2009) explored publicly available international guidelines and introduced the BIM framework, a research and delivery foundation for industry stakeholders”	(Lin, Su, & Chen, 2012)
95	Using a BIM maturity matrix to inform the development of AEC	Conference Paper July 2012	Extensive number of citations	(Shih, Sher, & Williams, 2012)

	Publication title	Type/Date	Context	Reference
	integrated curricula			
96	Cloud-based framework for the implementation of BIM	Journal Paper July 2012	Unknown – no access to Journal (Chinese portal)	(Qinghua, Haitao, Yongkui, & Lili, 2012)
97	An Integrated BIM Framework to Support Facility Management in Healthcare Environments	PhD Thesis August 2012	Single citation "Ontology has also been used for defining formal relationships and capture techniques and methodologies in BIM development (Succar, 2009)."	(Lucas, 2012)
98	An Activity Theoretical Approach to BIM-research	Book Chapter (103) Aug 2012	One quote	(Miettinen, Kerosuo, Korpela, Mäki, & Paavola, 2012)
99	A Utilization Approach of BIM for Integrated Design Process	Book Chapter (71) Aug 2012	Multiple citations and detailed quotations covering BIM Fields and BIM Stages	(Jadhav & Koutamanis, 2012)
100	BIM: In Search of the Organisational Architect	Journal Paper August 2012 final copy	"We posit that this technology – and the new related processes and policies (Succar, 2009)"…" Succar (2009) identifies three levels of supply chain transformation, moving from automating the BIM process within each firm, to breaking boundaries between firms, first through collaboration, then through integration."… "Model deliverables extend beyond semantic object properties to include business intelligence, lean construction principles, green policies and whole---lifecycle costing." (Succar, 2009: 365)"	(Forgues & Lejeune, 2013)
101	BIM Cube and Systems-of-Systems Framework	Book Chapter (55) August 2012	Multiple citations including "One of the most prominent and also inspiring for the BIM Cube was developed by Succar (2009), who developed a holistic multi-dimensional framework that is represented by a tri-axial knowledge model comprising of: BIM Fields of activity identifying domain 'players' and their 'deliverables'. These fields are represented on the x-axis, BIM Stages delineating implementation maturity levels (y-axis) and BIM Lenses providing the depth and breadth of enquiry necessary to	(Cerovsek, 2012)

Publication title		Type/Date	Context	Reference
			identify, assess and qualify BIM Fields and BIM Stages (z-axis)”	
102	BIM Practices and Challenges Framed – an Approach to Systemic Change Management	Book Chapter (65) Aug 2012	One citation “One well known framework illustrates the BIM approach as a tri-axial-model of BIM Stages, BIM Lenses and BIM Fields together with three interlocking fields of BIM Activities: policy field, process field and technology field. The aim for these frameworks has been to enable the stakeholders to understand underlying knowledge structures and negotiate BIM implementing requirements (Succar 2009)”	(Mäkeläinen, Hyvärinen, & Peura, 2012)
103	BIM Technologies and Collaboration in a Life-cycle Project	Book Chapter (113) Aug 2012	One generic citation	(Paavola, Kerosuo, Mäki, Korpela, & Miettinen, 2012)
104	Design and Software Architecture of a Cloud-based Virtual Energy Laboratory for Energy-efficient Design and Life Cycle Simulation	Book Chapter (2) Aug 2012	One citation although it may be inaccurately referencing the BIM ontology (assumed to be a schema not a conceptual ontology)	(Baumgärtel, Katranuschkov, & Scherer, 2012)
105	Integrated Collaborative Approach to Managing Building Information Modeling Projects	Book Chapter (69) Aug 2012	One generic citation	(Jadhav & Koutamanis, 2012)
106	Transportation System Architecture for Intelligent Management	Book Chapter (96) Aug 2012	One generic citation	(Szpytko, 2009)
107	BIM and Online Collaboration Platforms–An investigation into emerging requirements	Conference Paper Sep 2012	One generic citation	(Charalambous, Demian, Yeomans, Thorpe, Peters, & Doughty, 2012)
108	BIM Implementation Plans: a Comparative Analysis	Conference Paper Sep 2012	A few citations and quotations	(Ahmad, Demain, & Price, 2012)
109	Design of flexible and adaptable healthcare buildings of the future-a BIM approach	Conference Paper Sep 2012	One generic citation	(Krystallis, Demian, & Price, 2012)
110	A Framework for Measuring Building Information Modeling	Conference Paper Oct 2012	Several citations (including one for BIM Thinkspace) and comparisons with other ‘BIM maturity’	(Dib, Chen, & Cox, 2012)

	Publication title	Type/Date	Context	Reference
	Maturity Based on Perception of Practitioners and Academics Outside the USA		frameworks. "Succar's BIMMI offered a comprehensive framework based on a comparatively exhaustive review of previous research effort, however, areas for information management are kind of weak" – p. 246	
111	Boundaries Matter – The Pros and Cons of Vertical Integration in BIM Implementation	Book Chapter October 2012	Not known – no access to paper	(Lehtinen, 2012)
112	A Research Review on Building Information Modeling in Construction—An Area Ripe for IS Research	Journal Paper December 2012	"A framework designed to assess construction firms' readiness for BIM adoption in terms of IT competence and experience is presented by Succar [2009]" – p. 217	(Merschbrock & Munkvold, 2012a)
113	Information Integration and Collaborative Computation For Complex Structural Model	Journal Paper Dec 2012	Unknown – article is in Chinese, citation discovered through Google Scholar alerts	(Ball, Gui, Peng, & Hu, 2012)
114	Roadmap for implementation of BIM in the UK construction industry	Journal Paper Dec 2012	This paper is based on the structures introduced in the framework "The overarching methodology is based on the use of maturity concept using the Succar (2009) framework" – p. 613	(Khosrowshahi & Arayici, 2012)
115	Building information modeling como ferramenta de visualização de realidade aumentada em obras de reabilitação–um caso de estudo	Conference Paper December 2012	Citation listing the Benefits of BIM as identified within the BIM Framework paper	(Clements & Cachadinha, 2012)
116	BIM nas obras públicas em Portugal: Condicionantes para uma implementação com sucesso	Conference Paper December 2012	Extensive citations of BIM stages including the use of one visual model	(Taborda, 2012)
117	Towards Understanding BPR Needs for BIM Implementation	Journal Paper 2012	No access to article, requested from author	(Ayyaz, Ruikar, & Emmitt, 2012)
118	Adaptable buildings: A systems approach	Journal Paper 2012	One citation	(Gosling, Sassi, Naim, & Lark, 2012)
119	Aligning Building Information Model Tools and Construction	Journal Paper 2012	"Researchers (see for example Ref. [13]) have since long advocated that one of the main advantages of	(Hartmann, van Meerveld,

Publication title		Type/Date	Context	Reference
	Management Methods		the implementation of BIM based tools is the global improvement of all project processes for all organizations that work together on one construction project. Focusing on a number of business processes of one single organization within a project context might actually hinder the full leverage of all benefits on such a global project level.”	Vossebeld, & Adriaanse, 2012)
120	Application of Model Supported Collaboration In Information Technology for Construction Projects In The City Of São José Dos Pinhais	Master’s Thesis 2012	“Emerged in academic terms similar to nD Modelling and Integrated Design Systems, which changed its terminology to BIM in order to agree with the market reality (Succar, 2009)” – p. 86, translated from Portuguese using Google Translate	(Do Nascimento, 2012)
121	A Research Review on Building Information Modeling in Construction—An Area Ripe for IS Research	Journal Paper (revision, final version not available) 2012	“A framework designed to assess construction firms’ readiness for BIM adoption in terms of IT competence and experience is presented by Succar [2009]”	(Merschbro ck & Munkvold, 2012b)
122	BIM for Facilitation of Land Administration Systems in Australia	Report Section 2012	One generic citation	(Amirebrahi mi, 2012)
123	Course Outline, Masters of Project Management	Course Outline 2012	Article used as a ‘basic bibliographic reference’ for the course	(PPU, 2012)
124	Development of Model-based Process for Navigation Dredging	Master’s Thesis 2012	One generic citation	(Paukkeri, 2012)
125	Extension of Building Information Model for Disaster Mitigation: Using the Revit Platform	Master’s Thesis 2012	One citation – paper is in Chinese	(Lin, 2012)
126	Integration in the project development process of a Private Finance Initiative (PFI) project	Journal Paper 2012	One generic citation	(Kamara, 2012)
127	Physical Access Control Administration Using Building Information Models	Book Section 2012	One generic citation	(Skandhaku mar, Salim, Reid, & Dawson, 2012)
128	Towards Coordinated BIM based Design and Construction Process		Generic citations	(Lavikka, Smeds, & Smeds, 2012)
129	Utilisation of Building	Master’s	A couple of citations plus one graph	(Häkkinen,

	Publication title	Type/Date	Context	Reference
	Information Models in Production Organisation of Foundation Engineering	Thesis 2012	(in Finnish)	2012)
130	Expanding uses of building information modeling in life-cycle construction projects,	Journal paper 2012	Two citations covering the definition or a 'mature use of BIM' on pages 115 and 119	(Hannele et al., 2012)
131	A WebGL application based on BIM IFC	Master's Thesis 2012	"In other word, it is a way to digitally store and organise all the policies, processes, technologies, designs and projects concerning the life cycle of a building (Succar 2009)" p. 34	(Ferreira, 2012)
132	Building Information Modeling (BIM) Performance Assessment Framework for Organisations in the Singapore Construction Industry	Bachelor Thesis 2012	Extensive citation of several papers and industry publications	(Garvin, 2012)
133	Building information modelling in Denmark and Iceland	Journal Paper January 2013	"The findings from the questionnaire surveys presented in this paper could be used as benchmarks in such re-evaluations. It could also be interesting to relate the findings to frameworks for BIM maturity as presented for instance by Succar (2009).	(Per Anker & Elvar Ingi, 2013)
134	Building Information Modeling (BIM) partnering framework for public construction projects	Journal Paper January 2013	"However, at present, public sector is not ready with respect to the product, process, and people to position BIM adoption to the level of IPD [26]" "A coordinated BIM-Partnering framework for the design procurement is proposed with the following interrelated objectives: ….To provide a computational framework [26]"?!	(Porwal & Hewage, 2013)
135	Reinforcement Placement in a Concrete Slab Object Using Structural Building Information Modeling	Journal Paper February 2013	General citation…"Engineering, Construction, and Operations (AECO) industry (Succar, 2009) and can save time and cost and improve quality throughout the building's life cycle. BIM integrates the knowledge of AEC industries and academic research efforts using information technology (IT) and computer hardware"	(Cho, Lee, & Bae, 2013)
136	A research towards completing the asset information life cycle	Master's Thesis March 2013	A number of citations plus a referenced adaptation of one visual knowledge model	(De Vries, 2013)

	Publication title	Type/Date	Context	Reference
137	BIM implementation in organizational processes in construction companies - a case study	Master's Thesis March 2013 (in Portuguese)	References the three components of the BIM Framework (in Portuguese) – p. 16	(Parreira, 2013)
138	Performance measurement in the UK construction industry and its role in supporting the application of lean construction concepts	Journal Paper March 2013	"Ontology within BIM development has also been used to define formal relationships between elements (Succar, 2009)" – p. 78	(Sarhan & Fox, 2013)
139	The Integration of Architectural Design and Energy Modelling Software	PhD Thesis March 2013	Two generic citations plus an inaccurate quote "Succar (2009) describes BIM as a catalyst for change, predicted to reduce fragmentation in the AEC industry and improve efficiency/effectiveness" – p. 127	(Hetheringt on, 2013)
140	Changing building user attitude and organisational policy towards sustainable resource use in healthcare	Journal Paper April 2013	Generic citation	(Gulliver, Grzybek, Radosavljevi c, & Wiafe, 2013)
141	Cloud Computing for the Architecture, Engineering & Construction Sector: Requirements, Prototype & Experience	Journal Paper April 2013	Used as a reference only. No inline citations	(Beach, Rana, Rezgui, Parashar, & Cardiff, 2013)
142	Decision Making and Design Cognition in the age of Building Information Models	Bachelor Thesis April 2013	Generic citation within a footnote – p. 33	(Hanlon, 2013)
143	Implementing BIM techniques for energy analysis: a case study of buildings at university of la Laguna	Conference Paper April 2013	"Building Information Modeling is defined broadly as being "a set of interacting policies, processes technologies generating a methodology to manage the essential building design and project data in digital format throughout the building's life-cycle" (PENTTILÄ, 2006; SUCCAR, 2009)" - page 61	(Martin-Dorta, Assef, Cantero, & Rufino, 2013)
144	A Governance Approach for BIM Management across Lifecycle and Supply Chains Using Mixed-Modes of Information Delivery	Journal Paper April 2013	Three citations. However, the authors have misunderstood the essence of BIM Lenses and Filters and applied these to model views. The paper adopts 2 of 3 capability stages as bases for its governance model yet modifies/expands their connotations in a useful/usable	(Rezgui, Beach, & Rana, 2013)

Publication title		Type/Date	Context	Reference
			manner.	
145	A pilot model for a proof of concept healthcare facility information management prototype	Journal paper May 2013	"Ontology within BIM development has also been used to define formal relationships between elements (Succar, 2009)" – p. 78	(Lucas, Bulbul, & Thabet, 2013)
146	BIM-supported planning process for sustainable buildings–Process Simulation and Evaluation through Exploratory Research	Conference Paper May 2013	Generic citations – also cites the Five Components paper	(Kovacic, Oberwinter, & Müller, 2013)
147	Utilizing Building Information Models with Mobile Augmented Reality and Location-Based Services	May 2013	Generic Citation	(Nagy, 2013)
148	A Knowledge-Based Framework for Automated Space-Use Analysis	Journal Paper June 2013	"Frameworks have been developed and used in the construction industry either to view domain knowledge in an organized way [4–6] or to implement a novel method and facilitate its use [7–9]"- p. 166	(Kim, Rajagopal, Fischer, & Kam, 2013)
149	Analysis of BIM application relationship with integration degree of construction environment	Journal Paper June 2013	"Succar (2009) pointed out three levels for ID of BIM application – function application of single model, cooperative work of model-based and integrated application of life-cycle construction process." – p. 93	(Zhang, Tan, & Zhang, 2013)
150	A Practice oriented BIM framework and workflows	Conference paper June 2013	Several citations. The framework is used as a base to conduct data collection to develop another framework	(Kassem, Iqbal, & Dawood, 2013)
151	A survey on modeling guidelines for quantity takeoff-oriented BIM-based design	Journal Paper Available online June 2013	A generic citation	(Monteiro & Poças Martins, 2013)
152	Customer interactive building information modeling for apartment unit design	Journal Paper Available online June 2013	Generic citation	(Lee & Ha)
153	From justification to evaluation: Building information modeling for asset owners	Journal Paper Available online June 2013	Generic citation	(Love, Simpson, Hill, & Standing, 2013)
154	Building Information Modelling in the business of architecture: Case of Sweden	Master's Thesis June 2013	Extensive use of BIM fields and stages with adaptation of 2 visual knowledge models	(Majcherek, 2013)
155	Enhancing team integration in Building Information Modelling	Conference Paper June 2013	"Succar (2009), Philp (2012) and other authors (Eastman et al., 2011) agreed that implementation of BIM	(Hossain, Munns, & Rahman,

	Publication title	Type/Date	Context	Reference
	(BIM) projects.		involves fundamental change in the working procedure in the project delivery process; which is a cultural shift, the key challenge" p.81	2013)
156	Building Information Modelling and offsite construction In civil engineering	Conference Paper June 2013	"There are many (Succar, 2009, Sacks et al 2010) that believe BIM improves communication indirectly through its 3-D elements and visualisations, effectively communicating information on r spatial, logistical and material requirements" p.3	(Vernikos, Goodier, & Gibb, 2013)
157	O ensino de BIM no Brasil: onde estamos? (The teaching of BIM in Brazil where are we)	Journal Article June 2013	Multiple citations with a focus on BIM Stages (as relevant to BIM education)	(Ruschel, Andrade, & Morais, 2013)
158	Comparative Effectiveness of Quantity Surveying in a Building Information Modelling Implementation	Conference Paper June 2013	One citation of BIM term definition	(Kulasekara, Jayasena, & Ranadewa, 2013)
159	Identification of a Technological Framework for Implementing Building Information Modelling In Sri Lanka	Conference Paper June 2013	Two citations, one indirect quotation	(Gunasekara & Jayasena, 2013)
160	Assessing the BIM Maturity in a BIM Infant Industry	Conference Paper June 2013	Extensive citations and 1 model. A discussion of BIM stages and Bew-Richards BIM levels.	(Jayasena & Weddikkara, 2013)
161	Facilitating meaningful collaboration in architectural design through the adoption of BIM (Building Information Modelling)	Conference Paper June 2013	Generic citation	(Harty & Laing, 2013)
162	Factors affecting the current diffusion of BIM: a qualitative study of online professional network	Conference Paper July 2013	One citation – BIM definition	(Panuwatwanich & Peansupap, 2013)
163	BIM implementation: from capability maturity models to implementation strategy	Conference Paper July 2013	Extensive citations of BIM stages including an adaptation of a visual knowledge model. First paper to adopt the viDCO term. Also references the Five Components paper	(Sackey, Tuuli, & Dainty, 2013)
164	Beyond sharing: cultivating cooperative transportation systems through geographic information science	Journal Paper July 2013	Generic citation	(Miller, 2013)

Publication title		Type/Date	Context	Reference
165	Characteristics of Green BIM: Process and Information Management Requirements	Book Chapter July 2013	No access to chapter – citation discovered through Google Scholar alerts	(Gandhi & Jupp, 2013)
166	Incomplete BIM Implementation: Exploring Challenges and the Role of Product Lifecycle Management Functions	Book Chapter July 2013	No access to chapter – citation discovered through Google Scholar alerts	(Jupp, 2013)
167	Developing a Building Information Modelling Educational Framework for the Tertiary Sector in New Zealand	Book Chapter July 2013	No access to chapter – citation discovered through Google Scholar alerts	(Love et al., 2013)
168	Sustainable Construction Project Life-Cycle Management Based on Building Information Modeling	Conference Paper August 2013	Unknown – no access to content yet	(He, Wang, & Liu, 2014)
169	Development of Building Information Modelling Enabled Code Checking Systems for Australia	Conference Paper August 2013	Generic citation	(Shih & Sher, 2014)
170	Organisational readiness to implement building information modelling: A framework for design consultants in Malaysia	PhD Thesis August 2013	Multiple citations	(Haron, 2013)
171	Exploring the adoption of Building Information Modelling (BIM) in the Malaysian construction industry- a qualitative approach	Journal Paper August 2013	Generic and inaccurate citation "The United Kingdom (UK), the United States of America (USA), Singapore, Hong Kong, Australia and Denmark have established a policy whereby public construction projects are required to use BIM [34] and [16]." – page 392	(Zahrizan, Ali, Haron, Marshall-Ponting, & Abd, 2013)
172	Plumes: Towards a unified approach to building physical modeling	Conference Paper August 2013	One citation "The BIM covers an extensive range of assets (Succar, 2009)" – page 2831	(Robert, Delinchant, Hilaire, & Tanguy, 2013)
173	Construction Industry Products Diversification by Implementation of BIM	Journal Paper September 2013	No citation, just a reference in the bibliography	(Kalinichuk & Tomek, 2013)
174	The project benefits of Building Information Modelling (BIM)	Journal Paper October 2013	Three citations, mainly about BIM term definition…One quote "It has been defined as "a set of interacting policies, processes and technologies generating a methodology to manage the	(Bryde, Broquetas, & Volm, 2013)

Publication title		Type/Date	Context	Reference
			essential building design and project data in digital format throughout the building's life-cycle” (Succar, 2009: 357)	
175	Applications of GIS-Enhanced Networks of Engineering Information	Journal Paper October 2013	No access yet	(Sergi & Li, 2014)
176	A semiotic analysis of user interfaces of building information model systems	Journal Paper Available Online Sep 2013	“Contrary to this conceptualization of computer systems as semiotic knowledge encoding devices, researchers usually characterize BI software as systems to support the seamless information exchange between applications (Succar, 2009). These scholars have acknowledge the support of communication activities between different participants involved in a design and construction project as one of the main benefits that BI systems offer (Tomo and Cerovsek, 2011; Succar, 2009).” – page 5	(Hartmann)
177	Enhancing Knowledge Sharing Management Using BIM Approach in Construction	Journal Paper September 2013	General citation of the BIM Framework and the Five Metrics articles	(Ho, Tserng, & Jan, 2013)
178	Application of Earthquake Resistance Analysis Technique in the Design of Constructional Engineering	Journal Paper September 2013	Unknown – no access to content yet	(Gan & Luo, 2013)
179	Lessons From Using BIM to Increase Design-Construction Integration	Journal Paper September 2013	Inaccurate citation “Therefore, there have been numerous case studies identifying the benefits, and testing the capabilities and limitations of BIM (Barlish and Sullivan 2012; Sacks and Barack, 2008; Succar, 2009).” – page 4	(Luth, Schorer, & Turkan, 2013)
180	"BIM & cloud" management system security research	Journal Paper Sep 2013 In Chinese	Unknown – no access to content yet	(Xiaobo, 2013)
181	Novas demandas para as empresas de projeto de edifícios (New demands for building design firms)	Journal Paper Sep 2013	Two citations including “Succar (2009) defines the stages of evolution of the implementation of BIM and points to be worked for evolution to occur from one stage to another. The volume and complexity of the changes identified in the BIM stage, both organizational and industrial, are transformational and cannot be	(De Paula, Uechi, & Melhado, 2013)

	Publication title	Type/Date	Context	Reference
			implemented without an incremental evolution (Succar, 2009).” – page 139 as translated from Portuguese using Google Translate	
182	A distributed virtual reality application framework for collaborative construction planning using BIMserver	Conference Paper Oct 2013	Generic citation	(Zhou, Tah, & Heesom, 2013)
183	High-Performance Building Design and Decision-Making Support for Architects in the Early Design Phases	Licentiate Thesis Oct 2013	Generic citation	(Ren, 2013)
184	Construction waste management at source: a Building Information Modeling based system dynamic approach	PhD Thesis Nov 2013	Two inaccurate citations “However, at present, the public sector is not ready to accept BIM at the level of IPD (Succar et al., 2009)” – page 25, and “To provide a computational framework (Succar, 2009) that can be developed and implemented as an interactive computational BIM-Partnering design management tool to assist BIM managers and similar roles” – page 144.	(Porwal, 2013)
185	Early Implementation of Building Information Modeling into a Cold-Formed Steel Company: Providing Novel Project Management Techniques and Solutions to Industry	Journal Paper Nov 2013	Two citations “Penttila, (2006) appreciates that BIM is more than a 3D CAD system that creates a building’s geometrical data, but a methodology, essential to manage the project data in a digital format throughout the building’s lifecycle, this may be through interacting policies, processes and technologies [22]” – page 166. The other citation is more generic and refers to how BIM encourages waste reduction – page 170	(Barrett, Spillane, & Lim, 2013)
186	Early Implementation of BIM into a Cold-Formed Steel Design/ Fabricator and an Architectural/Planning Consultancy	Conference Paper Nov 2013	“Penttila, (2006) appreciates that BIM is more than a 3D CAD system that creates a building’s geometrical data, but a methodology essential to manage the project data in a digital format throughout the building’s lifecycle through interacting policies, processes and technologies (Succar, 2009)”	(Barett, Treacy, O'Reilly, Spillane, Lim, von Meding, Geary, Deary, & Booth, 2013)
187	Green BIM and Green Star certification practices: Case studies in commercial high-rise	Conference Paper Nov 2013	Generic Citation	(Ghandi & Jupp, 2013)

	Publication title	Type/Date	Context	Reference
	office design.			
188	Successfully implementing building information modelling in New Zealand: maintaining the relevance of contract forms and procurement models	Conference Paper Nov 2013	"Not only do a wide range of definitions of BIM exist but, as Succar (2009) presents, completely different terms are used all with the intent of describing BIM."	(Ryan, Miller, & Wilkinson, 2013)
189	Governance Model for Cloud Computing in Building Information Management	Journal Paper November 2013 (accepted for publication)	One citation "It has also become accepted that BIM should present the complete model of the building as a "phaseless" workflow [37]" – page 3	(Thomas, 2013)
190	BIM implementation throughout the UK construction project lifecycle: an analysis	Journal Paper December 2013	One generic citation: "From BIM stage 2 individual disciplinary BIM models within each discipline provided separately may be supplied at commissioning and handover [55]." – page 146	(Eadie, Browne, Odeyinka, McKeown, & McNiff, 2013)
191	Contractor practices for managing extended supply chain tiers	Journal Paper December 2013	Inaccurate citation "Succar (2009) showed that adoption of technologies such as BIM is limited as they are being evolved and have not reached to a maturity stage" – page 10 (of early cite document)	(Pala, Edum-Fotwe, Ruikar, Doughty, & Peters, 2014)
192	BIM Feasibility Study For Housing Refurbishment Projects In The UK.	Journal Paper December 2013	Generic citation	(Kim & Park, 2013)

Paper A3: Building Information Modelling Maturity Matrix

1	Building Information Modelling: Literature Review on Model to Determine the Level of Uptake by Organisation	Conference Paper May 2010	The ICMM limitation (a full page) plus two images are copied/referenced from the BIM Maturity Matrix Chapter.	(Haron et al., 2010)
2	Challenges to implementation of collaborative design process: analysis of human factor	Conference paper August 2010	"We sought to define three levels of maturity of BIM implementation in companies from the model (Succar, 2009) with reductions and simplifications. We understand that the full use of the model (Succar, 2009) can only be made from a sectoral approach in the AEC and a broad spectrum of respondents. According to the Brazilian reality the adoption of this model will require refinements and the introduction of other sub-levels of granularity before stage 1 as defined by the researcher." translated from Portuguese p.	(Manzione, Abaurre, Melhado, & Owen, 2011)
3	Tool for Benchmarking	Journal Paper	Extensive quotes yet arguing the	(Sebastian

Publication title		Type/Date	Context	Reference
	BIM Performance of Design, Engineering and Construction Firms in the Netherlands	November 2010	BIM Maturity Matrix can measure only organizational BIM and not the Product Model itself.	& Van Berlo, 2010)
4	Building Information Modeling in Local Construction Industry	Master Thesis December 2010	A few general citations	(Baba, 2010)
5	Design Process Communication Methodology	PhD Thesis June 2011	"While I did not add BIM maturity to my assessments of communication and complexity, I am confident that I could have used an assessment method such as the BIM Maturity Matrix (Succar 2010) to demonstrate that the effectiveness of product communication increased with increased usage of BIM"	(Senescu, 2011)
6	Benefits and ROI of BIM for Multi-Disciplinary Project Management	Undergraduat e Report March 2012	Heavily based on the BIM Maturity Index, Maturity Matrix and Scoring System. Survey developed based on the above and data then collected from industry.	(Qian, 2012)
7	Quality and Maturity of BIM Implementation within the AECO Industry	Conference Paper June 2012	Extensive citations	(Giel & Issa, 2012)
8	Toward Performance Assessment of BIM Technology Implementation	Conference Paper June 2012	Extensive referencing of the previous work in three articles: The BIM Framework, The BIM Maturity Matrix and The Five Components of BIM Performance Measurement (most citations are from the BIM Maturity Matrix)	(Mom & Hsieh, 2012b)
9	Using a BIM maturity matrix to inform the development of AEC integrated curricula	Conference Paper July 2012	Extensive number of citations. The BIM Maturity Matrix is used as a basis for assessing two case studies.	(Shih et al., 2012)
10	A Framework for Measuring Building Information Modeling Maturity in Construction Projects	Conference Paper October 2012	Extensive citations – more than 20 from the BIM Maturity Matrix and 1 from BIM ThinkSpace	(Chen, Dib, & Cox, 2012)
11	Construction Innovation and Process Improvement	Book 2012	"Frameworks for measuring BIM maturity can greatly facilitate organisations in positioning themselves against their Competitors in terms of technological, methodological and process maturity. Such a maturity framework is explained in Succar (201 0), where a five-	(Akintoye, Goulding, & Zawdie, 2012)

	Publication title	Type/Date	Context	Reference
			level BIM-specific maturity index is developed to measure the BIM maturity of organisations" (p. 400)	
12	Dictionary of Information Science and Technology	Dictionary 2012	8 dictionary terms are derived from the chapter: BIM Capability Stages, BIM Competency Sets, and BIM Fields, BIM Lenses, BIM Maturity Index (BIMMI), BIM Maturity Matrix, BIM Organizational Scales, and BIM Step – pp. 85 and 86	(Khosrowpour, 2012)
13	Building Information Modeling (BIM) Performance Assessment Framework for Organisations in the Singapore Construction Industry	Bachelor Thesis 2012	Extensive citation of several papers and industry publications	(Garvin, 2012)
14	Contemporary Strategies for Sustainable Design	PhD Thesis May 2013	One extensive citation of BIM nodes and stages – also references BIM Thinkspace episode 9	(Farias, 2013)
15	Synthesis of Existing BIM Maturity Toolsets to Evaluate Building Owners' BIM Competency	Conference Paper June 2013	Basic comparison of BIM maturity tools	(Giel & Issa, 2013)
16	Systems Engineering as a First Step to Effective Use of BIM	Book Chapter July 2013	No access yet – citation detected through Google Scholar	(Pels, Beek, & Otter, 2013)
17	Proposition for a Collaborative Design Process Management Conceptual Structure using BIM	PhD Thesis	Three models and a number of citations with a focus on BIM Stages and their effect on project lifecycle phases	(Manzione, 2013)
18	Organisational readiness to implement building information modelling: A framework for design consultants in Malaysia	PhD Thesis August 2013	Multiple citations	(Haron, 2013)
19	Research on Structure Model of Building Information Modeling Technology	Journal Paper September 2013	Unknown – journal not available. Citation reference appearing through Google email alerts	(Guo, 2013)

Paper A4: The Five Components of BIM Performance Measurement				
1	Open Information	Web page	"InPro generated the necessary	(INPRO,

Publication title		Type/Date	Context	Reference
	Environment for Knowledge-Based Collaborative Processes throughout the Lifecycle of a Building – What is Inpro	October 2010	knowledge to facilitate the construction industry to take a significant step to progress with BIM (refer to the implementation stages as described by Succar (Succar, B. (2010) The Five Components of BIM Performance Measurement, in: Proceedings of CIB World Congress, Salford, UK).” - section 2	2010)
2	Tool for Benchmarking BIM Performance of Design, Engineering and Construction Firms in the Netherlands	Journal Paper November 2010	Extensive quotes yet arguing that the BIM Maturity Matrix can measure only organizational BIM and not the Product Model itself	(Sebastian & Van Berlo, 2010)
3	Optimizing BIM Adoption and Mindset Change - Emphasize on a Construction Company	Master’s Thesis 2010	Several citations	(Mulenga & Han, 2010)
4	How to Measure the Benefits of BIM, a Case Study Approach	Master’s Thesis August 2011	Several citations and direct quotes	(Barlish, 2011)
5	BIM in Different Methods of Project Delivery	Conference paper October 2011	“These criteria were based on the main aspects of the BIM performance measurement tools used in The Netherlands and in the USA (Sebastian and Van Berlo 2010; Succar 2010)” p. 6	(Sebastian, 2011)
6	BIM – Adding Value By Assisting Collaboration	Conference Paper October 2011	General citation	(Macdonald, 2011)
7	On Decision-Making and Technology-Implementing Factors for BIM Adoption	Conference Paper Nov 2011	Multiple citations	(Mom et al., 2011)
8	Building Information Modeling Integrated with Electronic Commerce Material Procurement and Supplier Performance Management System	Master’s Thesis February 2012	Two figures and extensive citations covering BIM Fields, Capability and Maturity	(Ren, 2011)
9	How to measure the benefits of BIM — A case study approach	Journal Paper (based on Master’s Thesis) March 2012	Multiple citations and 1 figure	(Barlish & Sullivan, 2012)
10	BIM at Small Architectural Firms	Master’s Thesis April 2012	“The questions asked were based on the topics of the BIM Maturity Index by Succar (2010) and the BIM Quick Scan of TNO (Sebastian and van Berlo 2010)”	(Leeuwis, 2012)
11	Toward performance	Conference	Multiple citations of 3 papers	(Mom &

	Publication title	Type/Date	Context	Reference
	assessment of BIM technology implementation	Paper Jun 2012		Hsieh, 2012a)
12	Toward Performance Assessment of BIM Technology Implementation	Conference Paper June 2012	Extensive referencing of previous work in the BIM Framework, The BIM Maturity Matrix and The Five Components (most citations are from the BIM Maturity Matrix)	(Mom & Hsieh, 2012b)
13	BIM-Supported Lifecycle-oriented Design for Energy Efficient Industrial Facility - a Case Study	Conference paper June-July 2012	Generic citation	(Kovacic & Oberwinter, 2012)
14	Using a BIM maturity matrix to inform the development of AEC integrated curricula	Conference Paper July 2012	Extensive number of citations	(Shih et al., 2012)
15	BIM Anatomy An investigation into implementation prerequisites	Master's Thesis August 2012	References the use of DCO, closely adapts Project Lifecycle Phases without attribution. Copies an image from Episode 14 on BIMThinkSpace.com (with attribution) but without listing it in the bibliography	(Hooper, 2012)
16	Building Information Modeling (BIM) Performance Assessment Framework for Organisations in the Singapore Construction Industry	Bachelor Thesis 2012	Extensive citation of several papers and industry publications	(Garvin, 2012)
17	BIM-supported planning process for sustainable buildings–Process Simulation and Evaluation through Exploratory Research	Conference Paper May 2013	Generic citations – also cites the BIM Framework paper	(Kovacic et al., 2013)
18	Interdisciplinary, BIM-supported planning process	Conference Paper July 2013	Two inaccurate citations "In this context BIM addresses primarily the process of model-building and information exchange (Succar 2010)" and "Rather the design process itself needs to be organized (Succar 2010, Penttilä 2008)" – pages 2 & 3	(Oberwinter, Kovacic, Müller, Kiesel, Skoruppa, & Mahdavi, 2013)
19	BIM implementation: from capability maturity models to implementation strategy	Conference Paper July 2013	Extensive citations of BIM stages including an adaptation of a visual knowledge model. First paper to adopt the viDCO term. Also references the BIM Framework	(Sackey et al., 2013)

Paper A5: Measuring BIM performance: Five metrics

Publication title		Type/Date	Context	Reference
1	Using a BIM maturity matrix to inform the development of AEC integrated curricula	Conference Paper July 2012	Extensive number of citations	(Shih et al., 2012)
2	Improving Interorganizational Design Practices in the Wood-based Building Industry	Conference Paper June 2013	Used BIM Stages (pre-BIM, Stage 1 and Stage 2) for assessing the capability of research subjects. Sample citation: "From the discussion emerged that the organizations working in the wood-based building industry can be roughly classified into three levels of 'BIM capability' (Succar, 2012)" – p. 482	(Merschbrock & Munkvold, 2013)
3	Enhancing Knowledge Sharing Management Using BIM Approach in Construction	Journal Paper September 2013	General citation of the BIM Framework and the Five Metrics articles	(Ho et al., 2013)
Paper A6: An integrated approach to competency…				
	Published online June 20, 2013…no citations to date			
Paper B1: Building Information Modeling: analyzing noteworthy publications…				
	To be published in February 2014			
Paper B2: A proposed approach to comparing the BIM maturity of countries				
	Published October 12, 2013…no citations to date			
Paper C: BIM in Practice – BIM Education				
1	Exploring BIM-based education perspectives	Conference Paper Nov 2013	Extensive quotations…The paper is partially based on the BIM in Practice – BIM Education set of papers.	(Suwal, Jäväjä, Rahman, & Gonzalez, 2013)

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APPENDIX D

Focus groups info sheet and feedback form

FACULTY OF ENGINEERING
AND BUILT ENVIRONMENT

THE UNIVERSITY OF NEWCASTLE AUSTRALIA

Focus Group Feedback Form
Building Information Modelling Framework
Document Version 2.2 (17/05/2010)

Bilal Succar
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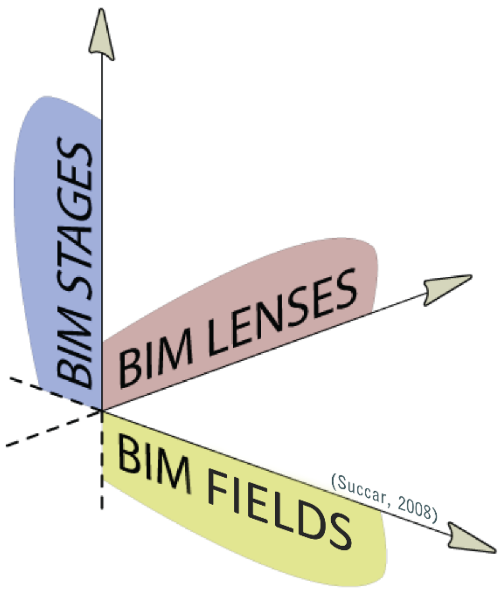


PART I: Participant Details (1 page)
PART II: Feedback Sheets (6 pages)

Please do not complete this anonymous feedback form before reviewing the **Research Project Information Statement** and signing the **Research Participant's Consent Form**

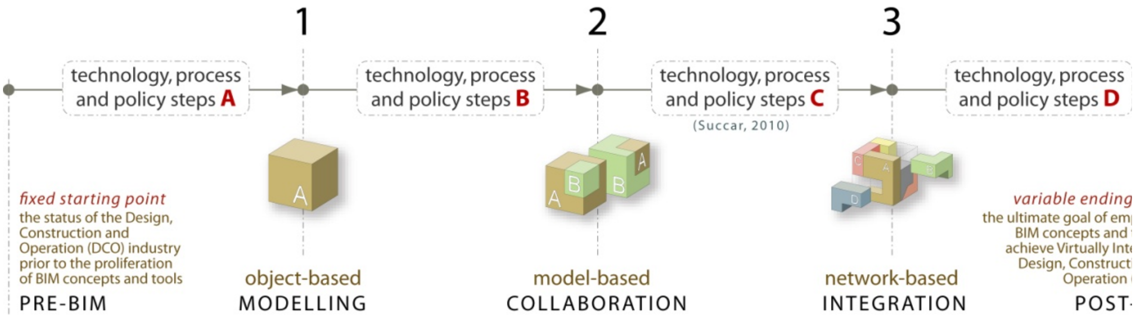
Please provide all applicable details to assist the researcher in contextualising your comments and suggestions. No personal information will be shared or disclosed. When completing this form, please use CAPITAL LETTERS as much as possible....Thank you.

Role within Industry (e.g. architect, engineer, contractor,...)	only if applicable
Role within Academia (e.g. researcher, lecturer,...)	only if applicable

Focus Group Location (Institution, City and Country)	e.g. RMIT UNIVERSITY, MELBOURNE AUSTRALIA
Focus Group Date (day/month/year)	e.g. 23/11/2010

BIM Capability Stages

Knowledge Model and Summary



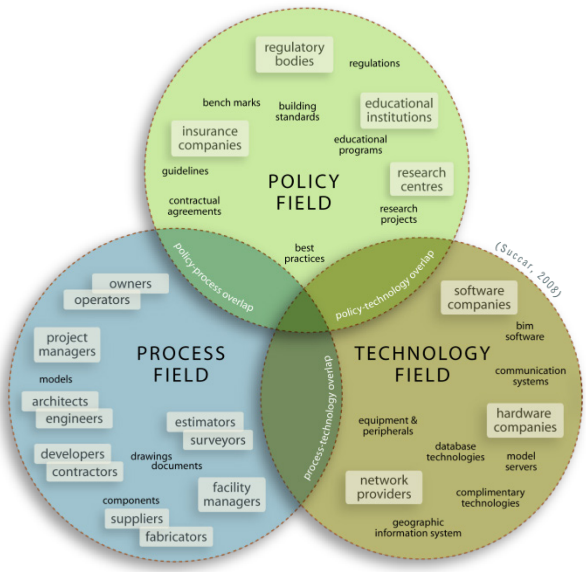
BIM Capability is the basic ability to perform a task or deliver a BIM service/product. BIM Capability Stages (or BIM Stages) define the *minimum BIM requirements*. BIM Stages identify a fixed starting point - the status before BIM implementation, three fixed BIM stages and a variable ending point which allows for unforeseen future advancements in technology.

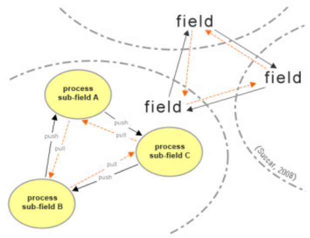
Feedback Section 1 (required)**:** Do you agree with the following statements?

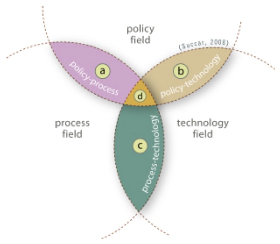
BIM Stages are clear and easy to understand	Strongly Agree ☐	Agree ☐	Neutral ☐	Disagree ☐	Strongly Disagree ☐
BIM Stages are accurate and representative	Strongly Agree ☐	Agree ☐	Neutral ☐	Disagree ☐	Strongly Disagree ☐
BIM Stages are usable for implementation, assessment and education	Strongly Agree ☐	Agree ☐	Neutral ☐	Disagree ☐	Strongly Disagree ☐
The knowledge model facilitates my understanding of BIM	Strongly Agree ☐	Agree ☐	Neutral ☐	Disagree ☐	Strongly Disagree ☐

Feedback Section 2 (optional)**:** Please provide additional written feedback or suggestions

Knowledge Model and Summary







BIM Fields are conceptual clusters of domain players *interacting* and *overlapping* within the AECO industry. There are three BIM Field Types (Technology, Process and Policy) and three Field Components (Players, Requirements and Deliverables).

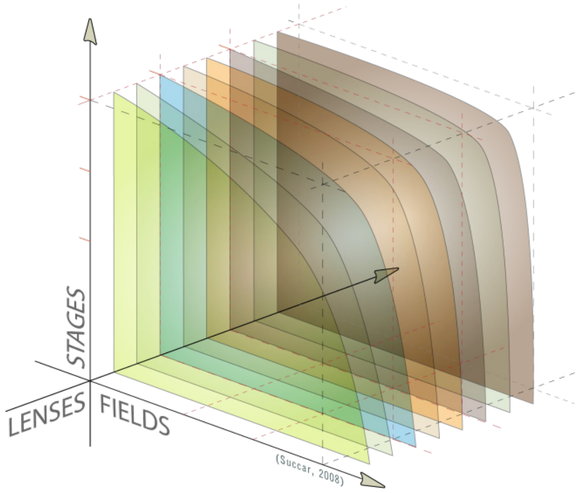
Feedback Section 1 (required)**:** Do you agree with the following statements?

BIM Fields are clear and easy to understand	Strongly Agree ☐	Agree ☐	Neutral ☐	Disagree ☐	Strongly Disagree ☐
BIM Fields are accurate and representative	Strongly Agree ☐	Agree ☐	Neutral ☐	Disagree ☐	Strongly Disagree ☐
BIM Fields are usable for implementation, assessment and education	Strongly Agree ☐	Agree ☐	Neutral ☐	Disagree ☐	Strongly Disagree ☐
The knowledge model facilitates my understanding of BIM	Strongly Agree ☐	Agree ☐	Neutral ☐	Disagree ☐	Strongly Disagree ☐

Feedback Section 2 (optional)**:** Please provide additional written feedback or suggestions

BIM Lenses

Knowledge Model and Summary



Sample Lenses:
Change Management
Construction/Project Management
Data Management
Design Management
Financial Management
Human Resource Management
Knowledge Management
Organisational Behaviour
Process Management
Quality Management
Product Management
Supply Chain Management
Risk Management

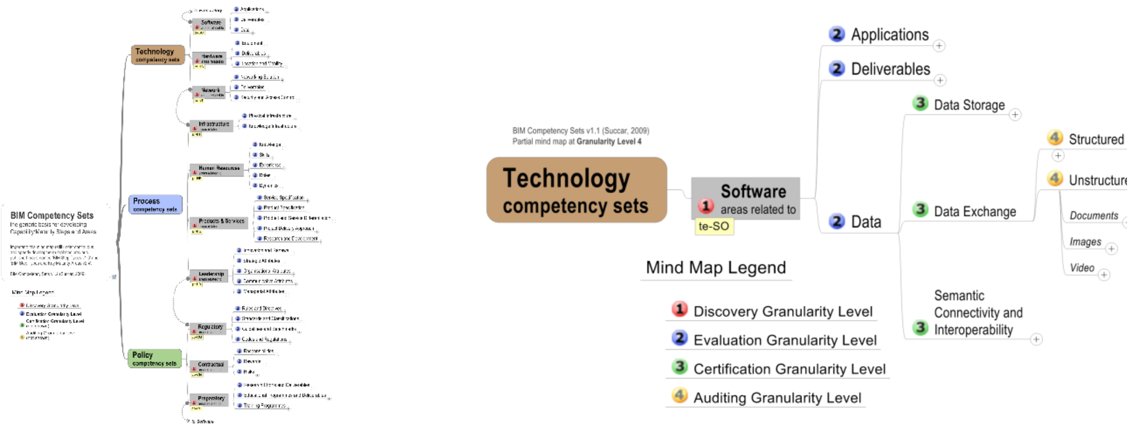
BIM Lenses represent the third dimension of the Framework and generate its depth of enquiry. BIM Lenses are distinctive layers of analysis which allow the researchers to selectively focus on any aspect of the AECO industry and generate knowledge views that either (a) highlight observables which meet the research criteria or (b) filter out those that do not.

Feedback Section 1 (required)**:** Do you agree with the following statements?

BIM Lenses are clear and easy to understand	Strongly Agree ☐	Agree ☐	Neutral ☐	Disagree ☐	Strongly Disagree ☐
BIM Lenses are accurate and representative	Strongly Agree ☐	Agree ☐	Neutral ☐	Disagree ☐	Strongly Disagree ☐
BIM Lenses are usable for implementation, assessment and education	Strongly Agree ☐	Agree ☐	Neutral ☐	Disagree ☐	Strongly Disagree ☐
The knowledge model facilitates my understanding of BIM	Strongly Agree ☐	Agree ☐	Neutral ☐	Disagree ☐	Strongly Disagree ☐

Feedback Section 2 (optional)**:** Please provide additional written feedback or suggestions

Knowledge Model and Summary



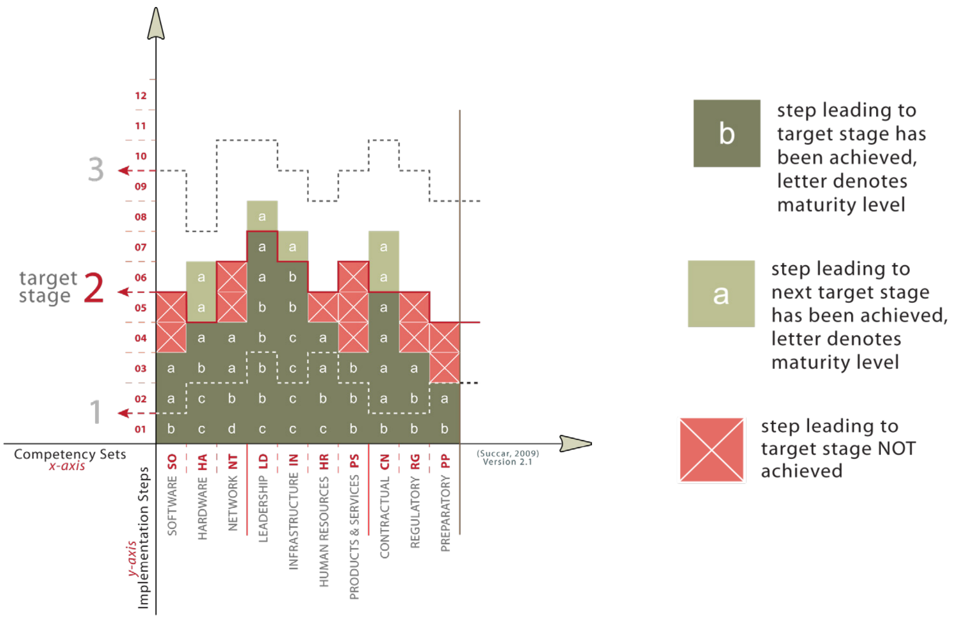
A BIM Competency Set is a hierarchical collection of individual competencies identified for the purposes of BIM implementation and assessment. If BIM Competency Set is used for active implementation, they are referred to as BIM Implementation Steps. However, if used for assessing existing implementations, they are referred to as BIM Assessment Areas.

Feedback Section 1 (required)**:** Do you agree with the following statements?

BIM Competencies are clear and easy to understand	Strongly Agree ☐	Agree ☐	Neutral ☐	Disagree ☐	Strongly Disagree ☐
BIM Competencies are accurate and representative	Strongly Agree ☐	Agree ☐	Neutral ☐	Disagree ☐	Strongly Disagree ☐
BIM Competencies are usable for implementation, assessment and education	Strongly Agree ☐	Agree ☐	Neutral ☐	Disagree ☐	Strongly Disagree ☐
The knowledge model facilitates my understanding of BIM	Strongly Agree ☐	Agree ☐	Neutral ☐	Disagree ☐	Strongly Disagree ☐

Feedback Section 2 (optional)**:** Please provide additional written feedback or suggestions

Knowledge Model and Summary



BIM Maturity is the ability to excel in performing a task or delivering a BIM service/product and its benchmarks (the five maturity levels) are performance improvement milestones for teams and organizations aspire to or work towards. The progression from low to higher levels of maturity indicate (i) better control through minimising variations between performance targets and actual results, (ii) better predictability and forecasting by lowering variability in competency, performance and costs, and (iii) greater effectiveness in reaching defined goals and setting new more ambitious ones

Feedback Section 1 (required)**:** Do you agree with the following statements?

BIM Maturity Levels are clear and easy to understand	Strongly Agree ☐	Agree ☐	Neutral ☐	Disagree ☐	Strongly Disagree ☐
BIM Maturity Levels are accurate and representative	Strongly Agree ☐	Agree ☐	Neutral ☐	Disagree ☐	Strongly Disagree ☐
BIM Maturity Levels are usable for implementation, assessment and education	Strongly Agree ☐	Agree ☐	Neutral ☐	Disagree ☐	Strongly Disagree ☐
The knowledge model facilitates my understanding of BIM	Strongly Agree ☐	Agree ☐	Neutral ☐	Disagree ☐	Strongly Disagree ☐

Feedback Section 2 (optional)**:** Please provide additional written feedback or suggestions

Comments or Suggestions

APPENDIX E

Statements of contribution

Co-author Statement

Reference: A1WS

As co-author of

A Proposed Framework to Investigate Building Information Modelling through Knowledge Elicitation and Visual Models,

I, **Willy Sher**, attest that this paper represents **Bilal Succar**'s original research and that he contributed all text, tables and figures.

Full name of co-author	Associate Professor William Sher, School of Architecture and Built Environment, University of Newcastle, NSW
Signature of co-author	
Date signed	14 June 2013

Signature of PhD candidate (Bilal Succar)	
Date signed	17.06.2013

Signature of primary supervisor (Associate Professor Willy Sher)	
Date signed	14 June 2013

Full name of the Assistant Dean Research Training (ADRT) University of Newcastle	M. Stockenhuber
Signature of ADRT	
Date signed	24. 6. 13

Please return **signed form** to PhD candidate by email to: Bilal.Succar@uon.edu.au
or by fax to: +613 9515 0031

Bibliographic reference: Succar, B., Sher, W., & Aranda-Mena, G. (2007). A Proposed Framework to Investigate Building Information Modelling Through Knowledge Elicitation and Visual Models. Paper presented at the Australasian Universities Building Education (AUBEA2007), Melbourne, Australia.

Reference: A1GAM

As co-author of

A Proposed Framework to Investigate Building Information Modelling through Knowledge Elicitation and Visual Models,

I, **Guillermo Aranda-Mena**, attest that this paper represents **Bilal Succar**
he contributed all text, tables and figures.

Full name of co-author	Associate Professor Guillermo Aranda-Mena, School of Property, Construction and Project Management, RMIT
Signature of co-author	
Date signed	June.13.2013

Signature of PhD candidate (Bilal Succar)	
Date signed	17.06.2013

Signature of primary supervisor (Associate Professor Willy Sher)	
Date signed	19 June 2013

Full name of the Assistant Dean Research Training (ADRT) University of Newcastle	M. STOCKENHUBER
Signature of ADRT	
Date signed	24.6.13

Please return **signed form** to PhD candidate by email to: Bilal.Succar@uon.edu.au
or by fax to: +613 9515 0031

Bibliographic reference: Succar, B., Sher, W., & Aranda-Mena, G. (2007). A Proposed Framework to Investigate Building Information Modelling Through Knowledge Elicitation and Visual Models. Paper presented at the Australasian Universities Building Education (AUBEA2007), Melbourne, Australia.

Co-author Statement

Reference: A5WS

As co-author of

Measuring BIM performance: Five metrics,

I, **Willy Sher**, attest that this paper represents **Bilal Succar**'s original research and that he contributed all text, tables and figures.

Full name of co-author	Associate Professor William Sher, School of Architecture and Built Environment, University of Newcastle, NSW
Signature of co-author	
Date signed	14 June 2013.

Signature of PhD candidate (Bilal Succar)	SUCCAR
Date signed	17.06.2013

Signature of primary supervisor (Associate Professor Willy Sher)	
Date signed	14 June 2013.

Full name of the Assistant Dean Research Training (ADRT) University of Newcastle	M. STOCKENHUBER
Signature of ADRT	
Date signed	24. 6. 13

Please return **signed form** to PhD candidate by email to: Bilal.Succar@uon.edu.au
or by fax to: +613 9515 0031

Bibliographic reference: Succar, B., Sher, W., & Williams, A. (2012). Measuring BIM performance: Five metrics. *Architectural Engineering and Design Management, 8*(2), 120-142. doi: 10.1080/17452007.2012.659506

Reference: A5AW

As co-author of

Measuring BIM performance: Five metrics,

I, **Anthony Williams**, attest that this paper represents **Bilal Succar** contributed all text, tables and figures.

Full name of co-author	Professor Anthony Williams, - Vice President (Research), Avondale College, NSW - School of Architecture of Architecture and Built Environment, University of Newcastle, NSW
Signature of co-author **Date signed**	Digitally signed by Professor Anthony Williams DN: cn=Professor Anthony Williams, o, ou, email=tony.williams@avondale.edu.au, c=<n Date: 2013.06.13 13:32:54 +10'00'

Signature of PhD candidate (Bilal Succar) **Date signed**	17.06.2013

Signature of primary supervisor (Associate Professor Willy Sher) **Date signed**	19 June 2013

Full name of the Assistant Dean Research Training (ADRT) University of Newcastle	M. STOCKENHUBER
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Date signed	25.6.13

Please return **signed form** to PhD candidate by email to: Bilal.Succar@uon.edu.au
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Bibliographic reference: Succar, B., Sher, W., & Williams, A. (2012). Measuring BIM performance: Five metrics. *Architectural Engineering and Design Management, 8*(2), 120-142. doi: 10.1080/17452007.2012.659506

Co-author Statement

Reference: A6WS

As co-author of

An integrated approach to BIM competency acquisition, assessment and application,

I, **Willy Sher**, attest that this paper represents **Bilal Succar**'s original research and that he contributed all text, tables and figures.

Full name of co-author	Associate Professor William Sher, School of Architecture and Built Environment, University of Newcastle, NSW
Signature of co-author	
Date signed	14 June 2013

Signature of PhD candidate (Bilal Succar)	SUCCAR
Date signed	17.06.2013

Signature of primary supervisor (Associate Professor Willy Sher)	
Date signed	14 June 2013

Full name of the Assistant Dean Research Training (ADRT) University of Newcastle	M. STOCKENHACUBER
Signature of ADRT	
Date signed	25. 6. 13

Please return **signed form** to PhD candidate by email to: Bilal.Succar@uon.edu.au
or by fax to: +613 9515 0031

Bibliographic reference: Succar, B., Sher, W., & Williams, A. (2013). An integrated approach to BIM competency acquisition, assessment and application. *Automation in Construction* (approved for publication)

Reference: A6AW

As co-author of

An integrated approach to BIM competency acquisition, assessment and application,

I, **Anthony Williams**, attest that this paper represents **Bilal Succar** contributed all text, tables and figures.

Full name of co-author	Professor Anthony Williams, - Vice President (Research), Avondale College, NSW - School of Architecture of Architecture and Built Environment, University of Newcastle, NSW
Signature of co-author	Digitally signed by Professor Anthony Williams DN: cn=Professor Anthony Williams, o, ou, email=tony.williams@avondale.edu.au, c=<n Date: 2013.06.13 13:35:37 +10'00'
Date signed	

Signature of PhD candidate (Bilal Succar)	
Date signed	17.06.2013

Signature of primary supervisor (Associate Professor Willy Sher)	
Date signed	19 June 2013

Full name of the Assistant Dean Research Training (ADRT) University of Newcastle	M. SEECKENHUBER
Signature of ADRT	
Date signed	24. 6. 2013

Please return **signed form** to PhD candidate by email to: Bilal.Succar@uon.edu.au
or by fax to: +613 9515 0031

Bibliographic reference: Succar, B., Sher, W., & Williams, A. (2013). An integrated approach to BIM competency acquisition, assessment and application. *Automation in Construction* (approved for publication)

Co-author Statement

Reference: B1MK

As the primary author of,

Building Information Modeling: Analyzing Noteworthy Publications of Eight Countries Using a Knowledge Content Taxonomy,

I, **Mohamad Kassem**, attest that **Bilal Succar** contributed to this chapter as follows:

- Developed a definition for noteworthy BIM publications (NBP)s;
- Provided the BIM knowledge content (BKC) taxonomy which was used to analyse NBPs;
- Identified 7 NBPs from AU and assessed those using the BKC; provided summary text for Australia;
- Provided Figure 1, 2 and Table 1; helped develop and populate Table 3 and Figures 3-5; and
- Edited and helped finalize the version submitted for review.

Full name of co-author	Associate Professor Mohamad Kassem, Technology Futures Institute, Teesside University, UK
Signature of co-author	
Date signed	11/06/2013

Signature of PhD candidate (Bilal Succar)	
Date signed	12.06.2013

Signature of primary supervisor (Associate Professor Willy Sher)	
Date signed	19 June 2013

Full name of the Assistant Dean Research Training (ADRT) University of Newcastle	H. STOCKENHUBER
Signature of ADRT	
Date signed	24.6.13

Please return **signed form** to PhD candidate by email to: Bilal.Succar@uon.edu.au
or by fax to: +613 9515 0031

Bibliographic reference: Kassem, M., Succar, B., & Dawood, N. (2013). Building Information Modeling: Analyzing Noteworthy Publications of Eight Countries Using a Knowledge Content Taxonomy In R. Issa & S. Olbina (Eds.), *Building Information Modeling: Applications and Practices in the AEC Industry*. University of Miami: ASCE (under review)

Co-author Statement

Reference: B1ND

As a co-author of,

Building Information Modeling: Analyzing Noteworthy Publications of Eight Countries Using a Knowledge Content Taxonomy,

I, **Nashwan Dawood**, attest that **Bilal Succar** contributed to this chapter as follows:

- Developed a definition for noteworthy BIM publications (NBP)s;
- Provided the BIM knowledge content (BKC) taxonomy which was used to analyse NBPs;
- Identified 7 NBPs from AU and assessed those using the BKC; provided summary text for Australia;
- Provided Figure 1, 2 and Table 1; helped develop and populate Table 3 and Figures 3-5; and
- Edited and helped finalize the version submitted for review.

Full name of co-author	Professor Nashwan Dawood, Director of Technology Futures Institute, Teesside University, UK
Signature of co-author	Nashwan
Date signed	11-06-13

Signature of PhD candidate (Bilal Succar)	Succar
Date signed	12.06.2013

Signature of primary supervisor (Associate Professor Willy Sher)	
Date signed	19 June 2013

Full name of the Assistant Dean Research Training (ADRT) University of Newcastle	M. Stockenhuber
Signature of ADRT	
Date signed	25. 6. 13

Please return **signed form** to PhD candidate by email to: Bilal.Succar@uon.edu.au or by fax to: +613 9515 0031

Bibliographic reference: Kassem, M., Succar, B., & Dawood, N. (2013). Building Information Modeling: Analyzing Noteworthy Publications of Eight Countries Using a Knowledge Content Taxonomy In R. Issa & S. Olbina (Eds.), *Building Information Modeling: Applications and Practices in the AEC Industry*. University of Miami: ASCE (under review)

Co-author Statement

Reference: B2MK

As the primary author of,

A proposed approach to comparing the BIM maturity of countries,

I, **Mohamad Kassem**, attest that **Bilal Succar** contributed to this chapter as follows:

- Developed a definition for noteworthy BIM publications (NBP)s;
- Developed the three metrics used to analyse NBPs – availability , distribution and relevance;
- Provided the BIM knowledge content (BKC) taxonomy;
- Provided Figures 1 and 5; helped develop and populate Tables 1-3; and
- Edited and helped finalize the version submitted for review.

Full name of co-author	Associate Professor Mohamad Kassem, Technology Futures Institute, Teesside University, UK
Signature of co-author	M Kassem
Date signed	11/06/2013

Signature of PhD candidate (Bilal Succar)	Succar
Date signed	12.06.2013

Signature of primary supervisor (Associate Professor Willy Sher)	
Date signed	19 June 2013

Full name of the Assistant Dean Research Training (ADRT) University of Newcastle	M. Stockenhuber
Signature of ADRT	
Date signed	25. 6. 13

Please return **signed form** to PhD candidate by email to: Bilal.Succar@uon.edu.au or by fax to: +613 9515 0031

Bibliographic reference: Kassem, M., Succar, B., & Dawood, N. (2013). A proposed approach to comparing the BIM maturity of countries. Paper presented at the 30th International Conference on Applications of IT in the AEC Industry - CIB W078, Beijing, China (under review)

Co-author Statement

Reference: B2ND

As a co-author of,

A proposed approach to comparing the BIM maturity of countries,

I, Nashwan Dawood, attest that **Bilal Succar** contributed to this chapter as follows:

- Developed a definition for noteworthy BIM publications (NBP)s;
- Developed the three metrics used to analyse NBPs – availability , distribution and relevance;
- Provided the BIM knowledge content (BKC) taxonomy;
- Provided Figures 1 and 5; helped develop and populate Tables 1-3; and
- Edited and helped finalize the version submitted for review.

Full name of co-author	Professor Nashwan Dawood, Director of Technology Futures Institute, Teesside University, UK
Signature of co-author	Nashwan
Date signed	11 - 06 - 13

Signature of PhD candidate (Bilal Succar)	Succar
Date signed	12.06.2013

Signature of primary supervisor (Associate Professor Willy Sher)	
Date signed	19 June 2013

Full name of the Assistant Dean Research Training (ADRT) University of Newcastle	R. Stockenhuff - Bell
Signature of ADRT	
Date signed	25. 6. 13

Please return **signed form** to PhD candidate by email to: Bilal.Succar@uon.edu.au
or by fax to: +613 9515 0031

Bibliographic reference: Kassem, M., Succar, B., & Dawood, N. (2013). A proposed approach to comparing the BIM maturity of countries. Paper presented at the 30th International Conference on Applications of IT in the AEC Industry - CIB W078, Beijing, China (under review)

Editor Statement

Reference: C2DH

As the former Chair of BIM/IPD Steering Group (2011-2013) and the overall editor the *AIA/CA BIM in Practice documents*,

I, **Dominik Holzer**, attest that **Bilal Succar** was the Chair of the BIM Education Working Group (EWG) which delivered the peer-reviewed BIM in Practice – BIM Education documents (referred to individually as E1, E2 and E3). The EWG included 11 members from both industry and academia and I understand that Bilal contributed significantly to the delivery of these documents as follows:

- Chaired the EWG over a 9 months period and co-ordinated the development of the BIM Education documents with EWG members, the Chairs of other working groups, and with me;
- Proposed, developed and illustrated the Collaborative BIM Education Framework, included in E3;
- Provided sample BIM competency hierarchies from his research and previous work; and
- Was the primary author of the three documents as peer-reviewed and published in 2012.

Full name of editor	Dr Dominik Holzer, Senior Lecturer, Digital Architectural Design at The University of Melbourne; former Chair of the AIA/CA BIM and IPD Steering Group (2011-2013)
Signature of editor	
Date signed	18 June 2013

Signature of PhD candidate (Bilal Succar)	
Date signed	18.06.2013

Signature of primary supervisor (Associate Professor Willy Sher)	
Date signed	19 June 2013

Full name of the Assistant Dean Research Training (ADRT) University of Newcastle	H. STOECKENHUBER
Signature of ADRT	
Date signed	28. 6. 2013

Please return **signed form** to PhD candidate by email to: Bilal.Succar@uon.edu.au
or by fax to: +613 9515 0031

Bibliographic reference: Succar, B., Agar, C., Beazley, S., Berkemeier, P., Choy, R., Giangregorio, R. D., Donaghey, S., Linning, C., Macdonald, J., Perey, R., & Plume, J. (2012). BIM in Practice - BIM Education, a Position Paper by the Australian Institute of Architects and Consult Australia. http://www.bim.architecture.com.au/

APPENDIX F

Compilation of all bibliographic references cited within the introduction document, submitted papers and preceding appendices

Appendix F: compiled bibliography v1.0

Building Information Modelling: conceptual constructs and performance improvement tools

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THANK YOU