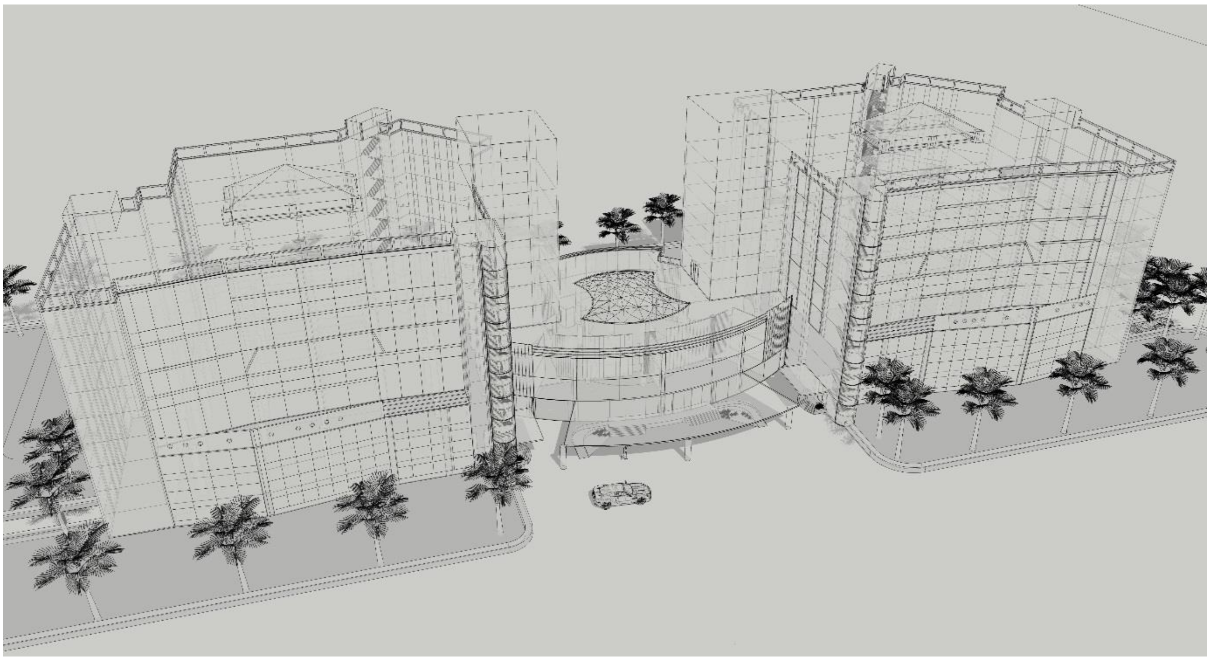
Building Information Modelling (BIM) and the Construction Industry

Technical Report (TR-1405A)



May 2014

JJ Ryan Consulting Pty Ltd
www.jjryan.com.au
ABN: 69 145 797 726

Version History

Version Number	Prepared By	Revision Date	Approved By	Approval Date	Description of Change
1.0	Jason Ryan	09/05/2014	Jason Ryan	19/06/2014	Initial release.

Use of this Report

This document has been prepared in good faith on the basis of information available at the date of publication without any independent verification. JJ Ryan Consulting Pty Ltd ("JJ Ryan Consulting") does not guarantee or warrant the accuracy, reliability, completeness or currency of the information in this publication nor its usefulness in achieving any purpose. Readers are responsible for assessing the relevance and accuracy of the content of this publication. JJ Ryan Consulting will not be liable for any loss, damage, cost or expense incurred or arising by reason of any person using or relying on information in this publication.

Products may be identified by proprietary or trade names to help readers identify particular types of products but this is not, and is not intended to be, an endorsement or recommendation of any product or manufacturer referred to. Other products may perform as well or better than those specifically referred to.

Executive Summary

Building Information Modelling (BIM) is a 3D digital representation of a building founded on open standards for interoperability and through its comprehension of spatial relationships.

This report has been prepared to provide an understanding of the role that BIM plays in modern society along with the impact of this technological development on society, the economy and the physical environment. It also explains the process by which society manages technological development of BIM and the role that managers of technology play in this process.

It has been determined that BIM has shifted the social interaction as well as roles and responsibilities of contractors involved in BIM. BIM technology has a substantial positive impact on modern society by increasing design and construction efficiency, as well as providing a safer work environment for construction workers. It is evident that the financial benefits realised by contractors utilising BIM has a flow-on effect throughout the construction industry and into the wider economy by contributing to productivity, maintaining global competitiveness and improving social wellbeing. BIM fosters innovation and the continuous sustainability through energy use reduction in building construction and operations, leading to a better built environment for end users, clients, and stakeholders.

It is evident that innovation of BIM technologies is a continuous and iterative system consisting of policies, processes and technology. These fields interact through push-pull mechanisms. It has been determined that early adopters and current leaders of BIM are the least to benefit from the technology, and there would be significant benefits in a shift towards owners / operators and contractors taking an active role in BIM leadership.

As industry continues to collaborate and “capability and maturity” models are developed and refined for architects, engineers, contractors and owners/operators (AECO) stakeholders, new and/or improved processes through well defined, measurable and monitored BIM phases (or stages or versions) will ultimately take account of all the three components of technology, processes and policy. It is evident that there is an increasing focus on developing an international standard and guidelines for the management of BIM.

It has been identified that various governments around the world are taking leadership with the implementation of BIM technologies by adopting policies in favour of BIM adoption. As attitudes towards BIM change, there will be a wider acceptance and adoption of BIM technology by contractors during construction. Attempts to improve progress tracking have recently focused on automation, using technologies such as 3D imaging, global positioning systems, ultra wide band indoor locating, handheld computers, voice recognition, wireless networks, and other technologies in various combinations.

It is envisaged that in the future, wearable augmented reality devices will alleviate the requirement to carry bulky construction drawings and reports to the site as well as reduce the effort required to obtain, store and retrieve construction data. It is also envisaged that other technologies currently used in project management systems will be incorporated with BIM technologies and that “As-Built” models will be delivered to owners / operators from point cloud data collected by laser scanners.

Table of Contents

EXECUTIVE SUMMARY II

1 INTRODUCTION 1

1.1 PURPOSE OF THIS TECHNICAL REPORT 1
1.2 TECHNOLOGICAL IMPACT AND MANAGEMENT 1
1.3 RESEARCH AND CRITICAL ANALYSIS METHODOLOGY 2
1.4 STRUCTURE OF THIS REPORT 2

2 BUILDING INFORMATION MODELLING 3

2.1 OVERVIEW OF BIM 3
2.2 HISTORY OF BIM 5

3 IMPACT ON THE CONSTRUCTION INDUSTRY 8

3.1 SOCIAL IMPACT 8
3.2 ECONOMIC IMPACT 10
3.3 ENVIRONMENTAL IMPACT 12

4 TECHNOLOGICAL MANAGEMENT OF BIM IN CONSTRUCTION 13

4.1 MANAGEMENT OF BIM IN CONSTRUCTION 13
4.2 EFFECTIVENESS OF BIM MANAGEMENT IN CONSTRUCTION 18

5 FUTURE OF BIM TECHNOLOGY 21

5.1 FUTURE OF BIM TECHNOLOGY 21
5.2 FUTURE OF BIM IN THE CONSTRUCTION INDUSTRY 25

6 CONCLUSIONS 27

7 RECOMMENDATIONS 29

LIST OF REFERENCES 30

List of Figures

Figure 2.1 – BIM system shown as the integration of AECOO stakeholders, people, process and information (Cholakis 2012)

Figure 2.2 – BIM deliverables throughout the life cycle of a building (Succar 2012)

Figure 2.3 – Development since the mid-1980's of models and products towards present-day BIM (Penttilä 2008)

Figure 3.1 –IEDF0 diagram of the model-based constructability review process (Wang & Leite 2012)

Figure 3.2 –Macleamy curve demonstrating the shift in effort from the construction phase into the design phase of the infrastructure's life cycle (Avramides 2012)

Figure 3.3 –Top five BIM benefits received by architects/engineers and contractors as a percentage receiving either "high" or "very high" benefits (MHC 2014)

Figure 3.4 –Construction productivity and the future project of productivity through BIM innovation (NIBS 2007)

Figure 3.5 –Perception of ROI of BIM by contractors (MHC 2014)

Figure 4.1 – Push-pull technology interactions between BIM fields and sub-fields (Succar 2013a)

Figure 4.2 – Detailed description of the process, policy and technology nodes in the management of BIM technology, applicable to contractors (Succar 2008a)

Figure 4.3 – Factors most likely to increase BIM benefits for contractors and architectural/engineering firms (MHC 2014)

Figure 4.4 – Capability maturity model (NIBS 2007)

Figure 4.5 – Adoption life cycle model of BIM technology

Figure 4.6 – Expected value of improvements due to BIM throughout the asset life cycle (Cholakis 2012)

Figure 4.7 – BIM industry leadership versus expected benefits (Succar 2010)

Figure 4.8 – Gartner Hype Cycle (Deutsch 2012)

Figure 4.9 – Rapid adoption of BIM technology by industry type (Deutsch 2012)

Figure 5.1 – Stages of BIIM (Succar 2008b)

Figure 5.2 – UK government's BIM road map (GCCG 2011)

Figure 5.3 – Hierarchy of Standards (NIBS 2007)

Figure 5.4 – Hierarchy of Standards (Cervosek 2011)

Figure 5.5 – Proposed BIM cube framework (Cerovsek 2011)

List of Tables

Table 2.1 – Various types of BIM models and their respective capabilities (adapted: Gee 2012)

Table 2.2 – Various types of activities and their use of respective types of models (adapted: Gee 2012)

Table 4.1 – Current BIM software providers and relevant products (adapted: Gee 2012)

Table 4.2 – Push-pull interactions between policy, process and technology for construction and contractors (adapted: Succar 2013a)

1 Introduction

1.1 Purpose of this Technical Report

The purpose of this technical report is to:

- Provide an understanding of the role that Building Information Modelling (BIM) plays in modern society;
- Assess the impact of the technological development of BIM on society, the economy and the physical environment; and
- Explain the process by which society manages technological development of BIM and the role managers of technology play in this process.

1.2 Technological Impact and Management

Modern society is based upon increasingly knowledge-intensive technology and innovation which is essential for delivering value to organisations and the wider economy (Bennett & Vaidya 2001). The acquisition of technological capability is based on a set of cumulative processes in which learning is derived from the development and use of technology. Bennett & Vaidya (2001) discuss that the accumulation of skills, experiences and technical know-how is essential for the long term development of national competitiveness, however these processes take time at all levels (including the level of the firm, industrial sectors and nation).

Cholakis (2012) identifies BIM as a set of previously disparate processes and technologies representing the physical and functional parameters of buildings to be digitally integrated. Hjelseth (2010) discusses that the typical stakeholders throughout the life cycle of a building include architects, engineers, contractors, owners / operators (AECO). BIM is divergent from the traditional antagonistic and inefficient architectural, design, engineering, construction and operations management process which have contributed to productivity inefficiencies in these sectors (Quirk 2012).

The diffusion of BIM throughout modern society is used to demonstrate the innovation processes observed such as “market pull” and “technology push”, the effects on the triple bottom line (society, economy and environment) as well as the role played by managers in adopting the new technology.

While the case study analyses the whole of life impacts of BIM (including during design, construction and operation), the focus of this technical report is on the role of construction contractors in the technological management of BIM and its impacts on construction.

1.3 Research and Critical Analysis Methodology

The historical, present and future use of BIM throughout the infrastructure life cycle has been researched to gain an understanding of BIM in modern society. This has enabled potential issues with management and impact of this technology in society to be fully determined, described and justified.

A literature review has been carried out to formulate alternatives or possible solutions with regards to effectiveness of the technological management of BIM. These have been derived from current research related to technological management of BIM and other types of technology. This research has included reviewing journal articles, text books, international standards and other relevant sources. The solutions that have been identified have been provided in the form of recommendations that have details of an implementation plan that could be put in place to achieve the recommendations.

1.4 Structure of this Report

Section 2 of this technical report defines BIM and describes its history from creation to the present. Section 3 assesses the impact of BIM in the construction industry with respect to social, economic and environmental effects. Section 4 describes how BIM has been managed in the construction industry and analyses whether the management of BIM in the construction industry has been effective. Section 5 analyses possibilities for the future use of BIM as well as how BIM is likely to change the future of the construction industry.

Section 6 of this technical report provides a conclusion of the findings from the review of BIM and its impact on and management within the construction industry, including whether the management of BIM has been effective as well as the potential future uses and impacts of BIM on the construction industry.

Section 4 of this technical report provides a series of recommendations based upon the conclusions with an appropriate implementation plan for consideration on the future of technological management of BIM.

2 Building Information Modelling

2.1 Overview of BIM

The National BIM Standard Definition (NIBS 2007) states that a BIM is a:

> *"… digital representation of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life cycle from inception onward".*

To optimise the return on investment and associated impacts upon the environment, stakeholders may be involved in a single aspect or multiple aspects of a BIM system (Cholakis 2012) including design, procurement, construction delivery methods, construction management, condition assessment, repair, renovation, adaptation, utilisation, capital planning and budgeting, life/safety and security management.

The BIM system is a collaboration by different stakeholders at different phases of the life cycle of a facility to insert, extract, update or modify information in the BIM to support and reflect the roles of that stakeholder (NBIS 2007). Figure 2.1 summarises the BIM system as the integration of the AECO stakeholders through the utilisation of people, processes and systems.

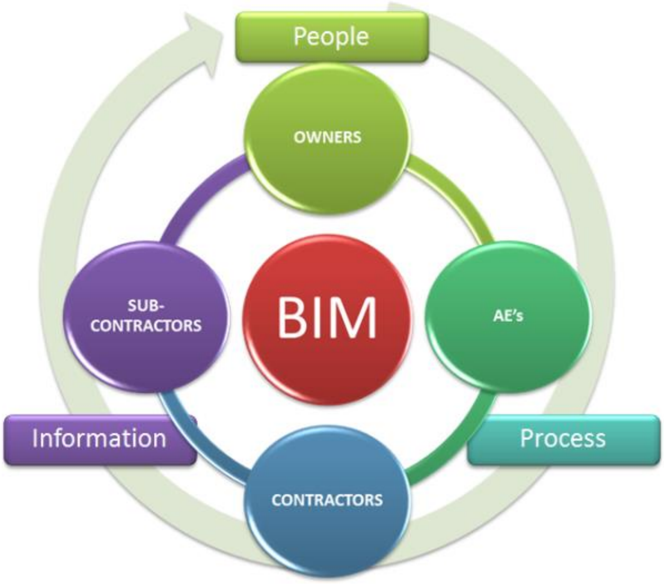


Figure 2.1 – BIM system shown as the integration of AECOO stakeholders, people, process and information (Cholakis 2012)

This shared BIM is a digital representation founded on open standards for interoperability and through its comprehension of spatial relationships. It is suggested that a BIM can meaningfully represent and integrate previously isolated control and management systems and processes, and thereby provide a more intuitive interface to users (Skandhakumar et. al. 2012). Succar (2013a) summarises the potential benefits of BIM during the whole life cycle of a facility, including design, construction and operation in Figure 2.2.

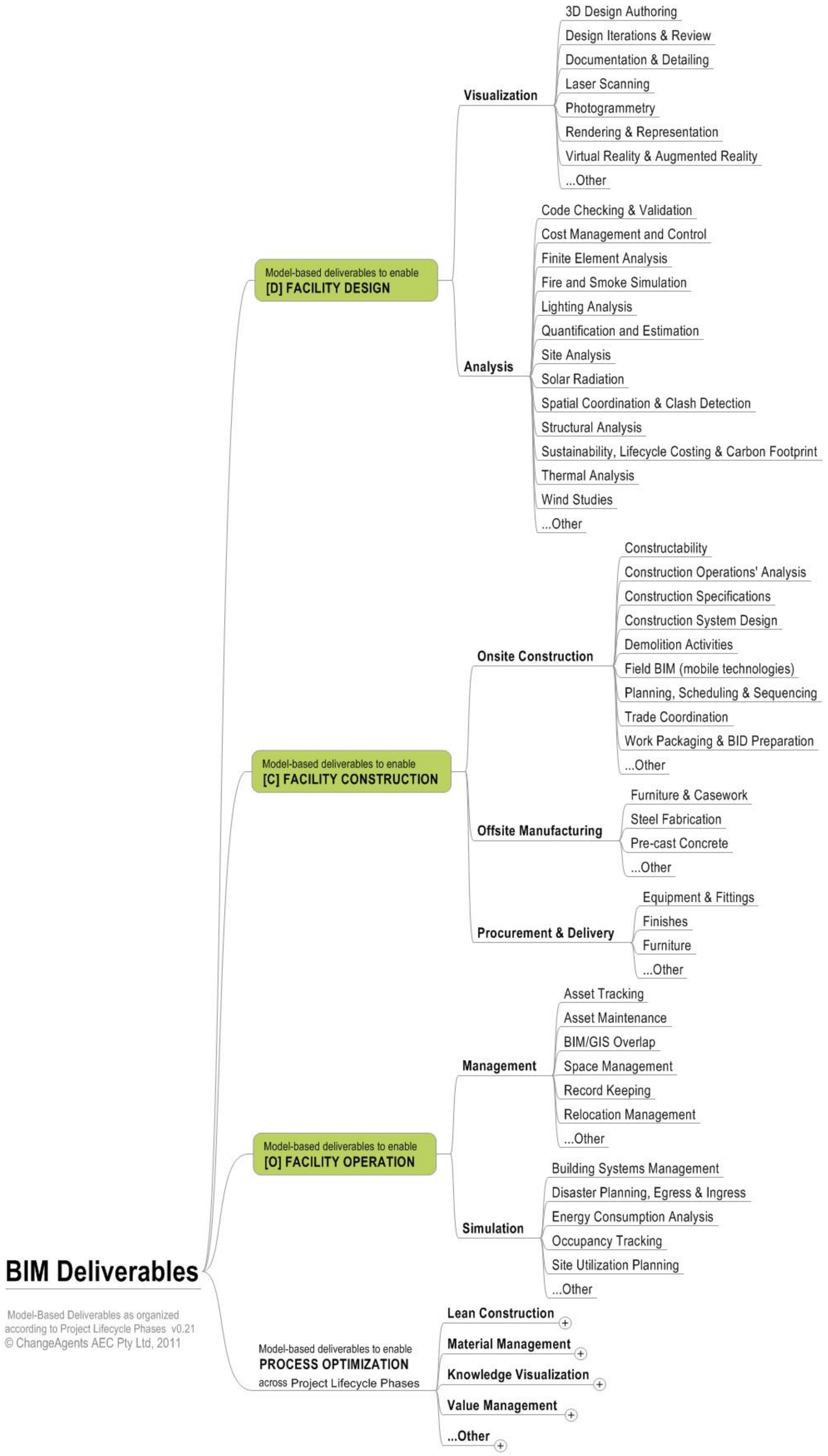


Figure 2.2 – BIM deliverables throughout the life cycle of a building (Succar 2012)

2.2 History of BIM

Quirk (2012) discusses that the conceptual underpinnings of BIM were identified as early as 1962 by Douglas C. Englebart (an American engineer, inventor, and an early computer and internet pioneer). Engelbart (1962) provided an uncanny vision for the future management of information in design in his paper “Augmenting Human Intellect: A Conceptual Framework”. The objective of Engelbart’s (1962) study was to:

> *“… develop a conceptual framework within which could grow a coordinated research and development program whose goals would be the following:*
>
> *(1) to find the factors that limit the effectiveness of the individual's basic information-handling capabilities in meeting the various needs of society for problem solving in its most general sense; and*
>
> *(2) to develop new techniques, procedures, and systems that will better match these basic capabilities to the needs' problems, and progress of society.”*

The ideas and concepts relevant to BIM have been apparent since the earliest days of computing with previous evolutions of BIM during the 1970's including computer models for buildings, building product models and product data models. An elementary foundation for a BIM which has a close connection with architectural design and engineering practices is the requirement for graphical user interface and the description of three-dimensional (3D) geometry (Penttilä 2008).

Quirk (2012) discusses that there is a long list of design researchers whose influence was considerable in developing technologies towards BIM including Herbert Simon, Nicholas Negroponte and Ian McHarg who were developing a system in parallel to BIM which is now known as Geographic Information Systems (GIS).

In 1963, Ivan Sutherland developed Sketchpad (also known as Robot Draftsman) which was revolutionary computer program that was considered to be the ancestor of modern computer-aided drafting (CAD) programs (Sears & Jacko 2007).

During the 1970’s and 1980’s two main methods of displaying and recording shape information were Constructive Solid Geometry (CSG) and Boundary Representation (BREP). During this period, solid modelling programs began to appear building on developments in the computational representation of geometry (Quirk 2012).

Charles Eastman (who was trained as an architect) identified that a building system is the spatial composition of a set of parts (Eastman et. al. 1974). Eastman et. al. (1974) proposed a Building Description System (BDS) to allow for easy graphic entering of arbitrarily complex element shapes; provision of an interactive graphic language for editing and composing element arrangements; provision of hardcopy graphic capabilities that can produce perspective or orthographic drawings of high quality; as well as allow sorting and formatting capabilities of the database by attributes (for example by material type, supplier or composing a data set for analysis).

Eastman et. al (1974) criticised hardcopy drawings for their tendency to decay over time as well as their failure to represent the building as renovations occurred. This resulted in the emergence of the notion for automated model reviews to "check for design regularity". It was concluded that BDS would reduce the cost of design, through "drafting and analysis efficiencies" by more than 50% (Quirk 2012).

Quirk (2012) describes several systems that were developed in the United Kingdom (UK) in the early 1980's that applied to construction projects Graphic Data Systems (GDS), Edinburgh Computer-Aided Architectural Design (EdCAAD), Cedar, Really Universal Computer Aided Production System (RUCAPS) followed by Sonata and Reflex.

Similar developments were underway in other parts of Europe with the development of ArchiCAD in 1982. The co-founder and founder of Revit and ArchiCAD (Leonid Raiz and Gábor Bojár respectively) based in Hungary were using similar technology as Eastman's (1974) BDS. The software Radar CH was released in 1984 for the Apple Lisa Operating System which later became ArchiCAD (the first CAD software available on a personal computer) (Quirk 2012).

Parametric Technology Corporation (PTC) was founded in 1985 and released the first version of Pro/ENGINEER in 1988 (Quirk 2012). This is a mechanical CAD program that utilises a constraint based parametric modelling engine. Equipped with the knowledge of working on Pro/ENGINEER, Irwin Jungreis and Leonid Raiz split from PTC and started their own software company called Charles River Software in the United States of America (USA).

Since the development of these early technologies there have been various university and industry collaborations to further the development of BIM. Figure 2.3 provides a summary of the progress of models, product models and product data models since from the 1980's towards modern day BIM systems (Penttilä 2008).

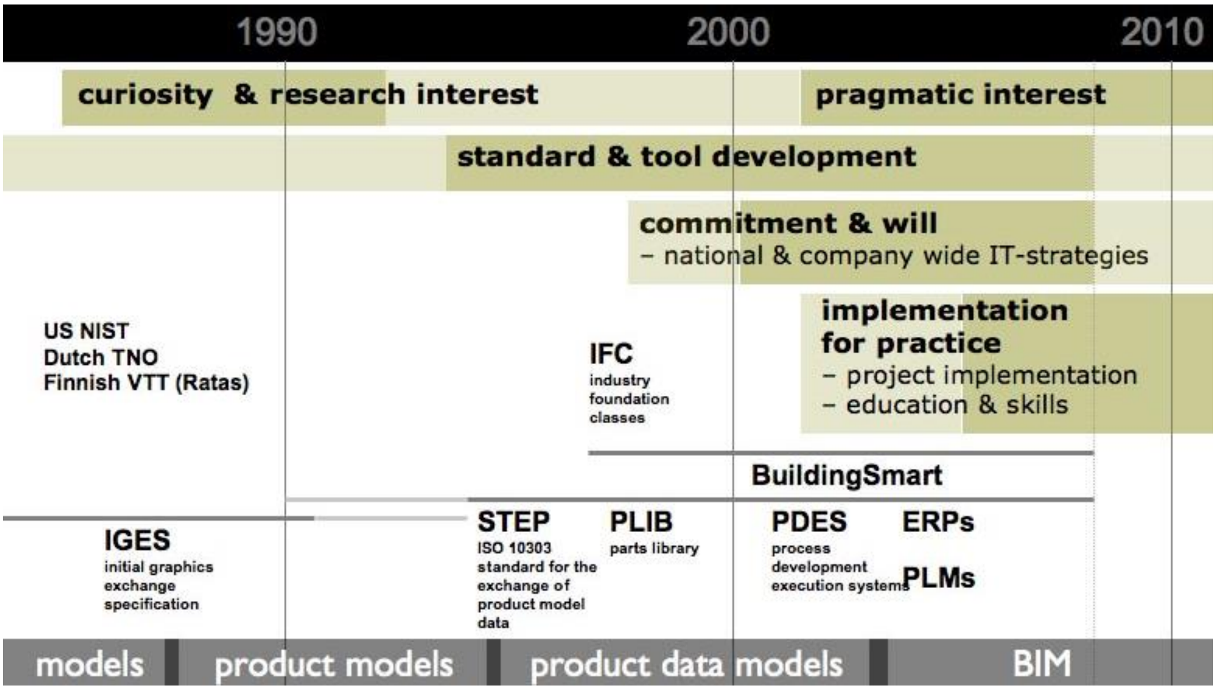


Figure 2.3 – Development since the mid-1980's of models and products towards present-day BIM (Penttilä 2008)

Quirk (2012) discusses that by the year 2000, a program called "Revit" was developed which made object oriented programming possible. In 2002, Autodesk purchased Revit and began to heavily promote the software in competition with its own object-based software "Architectural Desktop". The ability to assign a time attribute to individual components allows construction schedules to be developed based on the BIM (known as the "fourth-dimension" or 4D). These 4D models are used to simulate the construction process as well as allow real-time cost estimation and material quantity take-offs.

Gee (2012) discusses various uses for BIM tools such as client decision making, design and engineering, pre-construction and estimating, scheduling, constructability analysis, construction coordination, and post-construction. Efforts are under way to help standardise the use of BIM and related tools to help the industry streamline sharing of project information and therefore reduce duplication while helping stakeholders to avoid issues and conflicts on projects. An example of a system developed is the International Foundation Class (IFC) file format which was developed in 1995 and has continued to adapt to allow the exchange of data from one BIM program to another (Quirk 2012).

Additional tools have been integrated with BIM which are considered additional "dimensions". Table 2.1 summarises the differences between the capabilities of 3D, 4D, 5D and 6D BIM systems. Table 2.2 is a matrix that demonstrates the various uses of the different model types (Gee 2012).

Table 2.1 – Various types of BIM models and their respective capabilities (adapted: Gee 2012)

Model Type	Model Description
3D Models	▪ Building models that provide the perception of depth ▪ Building Systems Coordination ▪ Architectural / Structural, MEPF Clash Detection ▪ Construction Sub-Trade Coordination
4D Models	▪ Combines 3D models with the appropriate scheduling data ▪ Model Based Construction Simulation ▪ Project and Manpower Scheduling
5D Models	▪ Combines 3D models with the appropriate cost data ▪ Model-based Quantity Take-offs and Estimating ▪ Performance Based Value Engineering
nD (or 6D) Models	▪ Combines 3D models with the life cycle management data ▪ Energy Life Cycle and Daylighting Performance Modeling ▪ Virtual As-Builts with Hyperlinked product data, warranties, O&Ms, and manufacture's web sites

Table 2.2 – Various types of activities and their use of respective types of models (adapted: Gee 2012)

	Model Type				
Activity Description	**2D**	**3D**	**4D**	**5D**	**nD**
Client decision making	✓	✓			✓
Design and engineering		✓	✓		✓
Pre-construction and estimating		✓	✓	✓	
Scheduling		✓	✓		
Constructability analysis			✓		
Construction coordination				✓	
Post-construction					✓

3 Impact on the Construction Industry

A buildingSMART Australasia (2012) report states that poor documentation of construction projects was leading to an inefficient, non-competitive industry; cost overruns, rework, extensions of time; high stress levels, loss of morale, reduced personal output; adversarial behaviour, diminished reputations and a decline in safety standards.

BIM tools are anticipated to become the primary means of information exchange between the various stakeholders involved in construction projects as the exchange of design models evolves away from 2D CAD and paper towards semantically-rich 3D digital models (Steel et. al. 2012).

The effects of BIM tools on the sustainability triple-bottom line (social, economic and environmental) due to the exchange of construction information using BIM are discussed below as the industry endeavours to move further towards fully digitised information exchange.

3.1 Social Impact

Melzner et. al. (2012) found that safety on construction sites is a world-wide issue with the construction industry experiencing one of the highest occupational accident rates. Wang and Leite (2012) discuss that information technologies such as BIM and Virtual Design and Construction (VDC) have been increasingly used to improve management efficiency in the construction industry by integrating constructability assessments during the design phase.

Avramides (2012) observes that there has been a shift in the concentration of effort into the earlier stages of design. Contractors and sub-contractors are now, more than ever involved in the design phases to assist in the development of building documentation. Figure 3.1 demonstrates the BIM based constructability review process (Wang & Leite 2012).

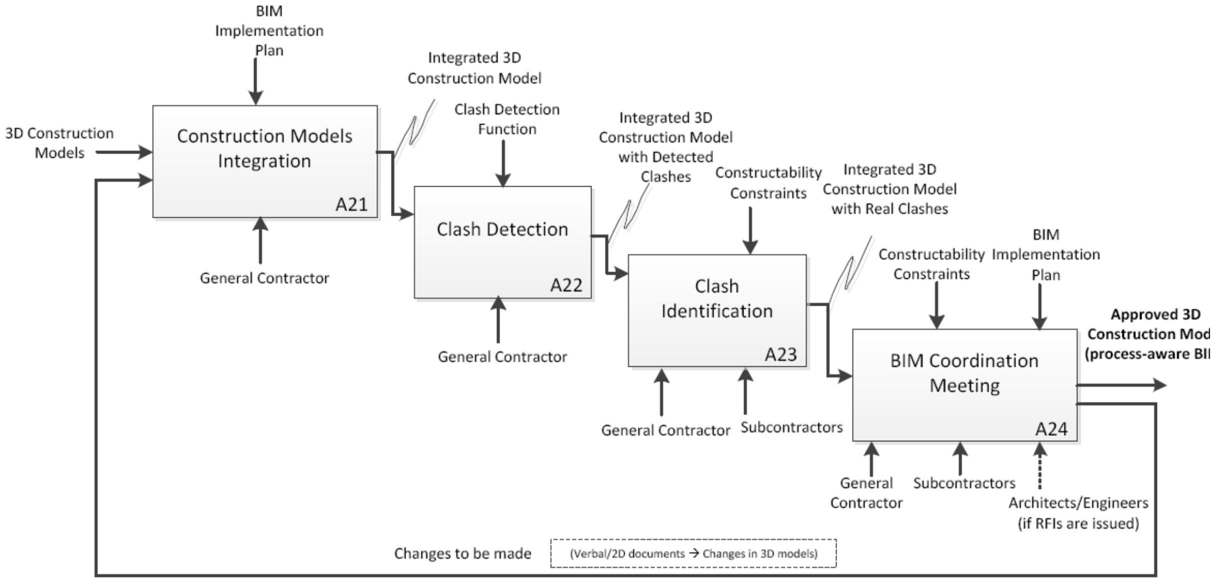


Figure 3.1 –IEDF0 diagram of the model-based constructability review process (Wang & Leite 2012)

Through detailed computer visualisation of each element of the total building system, BIM is used to reduce and prevent potential errors by design team members by allowing the conflict detection (where the computer informs designers or contractors about elements of the building that are in conflict or clashing) (Wang & Leite 2012).

Figure 3.2 demonstrates the shift in effort from the traditional method for design construction versus the integrated design and construction method using BIM systems. It is demonstrated that there is more effort required during the earlier stages of design when there is the greatest opportunity to influence costs to the project. The new processes now require modern contractors to have greater input into the design phase of infrastructure life cycle (Avramides 2012) and to ownership of the design.

Zhang et. al. (2013) have developed an automated safety checking platform to inform construction engineers and managers by reporting, why, where, when, and what safety measures are needed for preventing fall-related accidents before construction starts. The BIM tool automatically identifies and corrects hazards during construction planning and in certain cases during design.

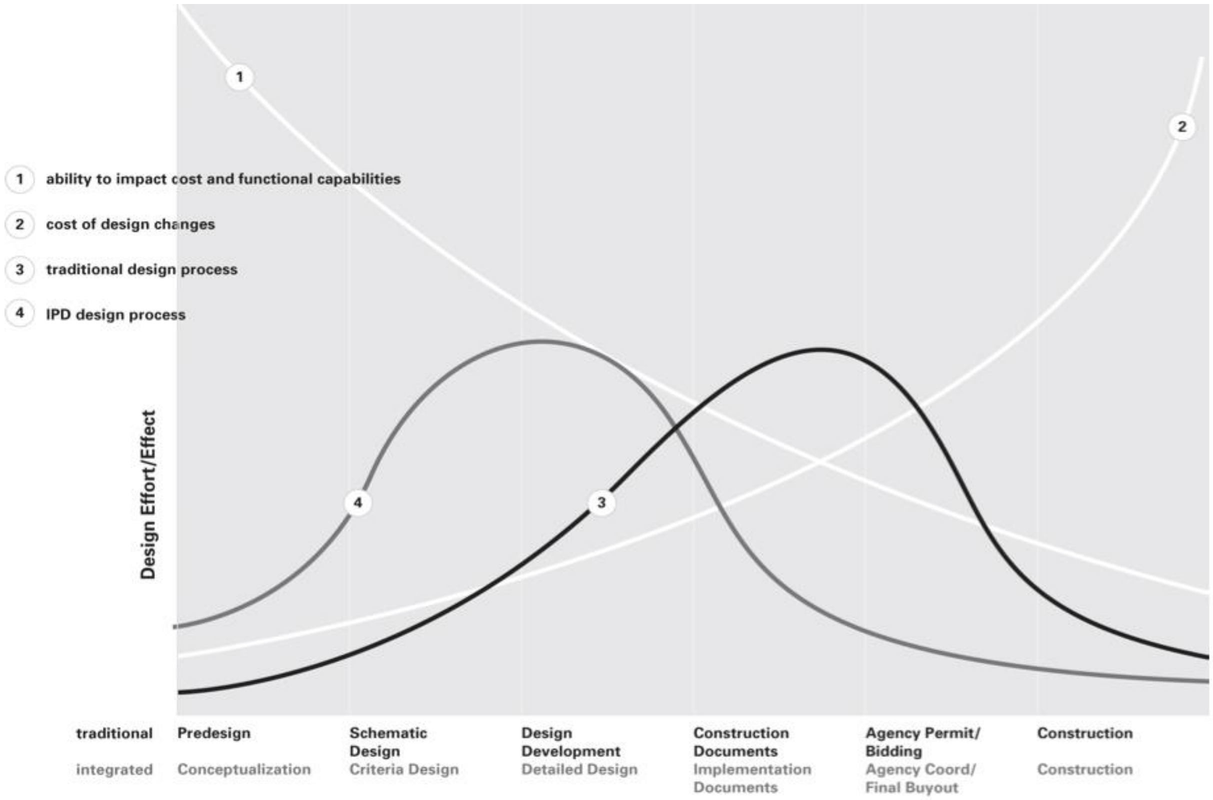
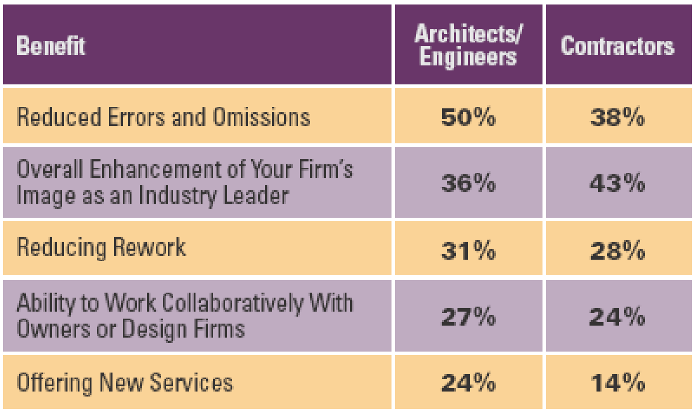


Figure 3.2 –Macleamy curve demonstrating the shift in effort from the construction phase into the design phase of the infrastructure's life cycle (Avramides 2012)

The role of BIM in safety design and planning demonstrates that BIM based safety planning can change the work flow in work perpetration for construction sites, particularly in comparison to the traditional safety decision making processes for occupational safety (Zhang et. al. 2013). An additional benefit of changes to the workflow is that more items will be pre-assembled (prefabricated) off-site and trucked to the site, therefore keeping the on-site trades to a minimum (MHC 2014).

Figure 3.3 demonstrates the top five BIM benefits received by architects/engineer firms and contractors (as a percentage receiving either a “high” or “very high” level benefit) (MHC 2014). It is demonstrated that 43% of contracting firms believe that the use of BIM on their projects enhances their image as an industry leader and a further 14% of contractors are using BIM to offer new services.



Benefit	Architects/ Engineers	Contractors
Reduced Errors and Omissions	50%	38%
Overall Enhancement of Your Firm’s Image as an Industry Leader	36%	43%
Reducing Rework	31%	28%
Ability to Work Collaboratively With Owners or Design Firms	27%	24%
Offering New Services	24%	14%

Figure 3.3 –Top five BIM benefits received by architects/engineers and contractors as a percentage receiving either “high” or “very high” benefits (MHC 2014)

Discipline-specific knowledge and tracking of changes are captured in single as it is passed between AECO stakeholders. This has resulted in shifts in the social interaction as well as roles and responsibilities of the contractors involved with BIM. A significant proportion of construction firms have recognised that BIM enhances a contractor’s reputation as an industry leader.

It is evident that BIM technology has a substantial a positive impact on modern society by increasing design and construction efficiency, as well as providing a safer work environment for construction workers. It can be seen that the use of BIM in safety in design has the potential to increase the safety of buildings throughout a building’s entire life cycle.

3.2 Economic Impact

The construction industry in the USA has experienced a gradual decrease in its labour productivity since the early 1960’s while non-farm industries such as the manufacturing industry have increased their labour productivity. The reduction of labour productivity in the construction industry requires more labour hours per contract dollar amount (Hergunsel 2011).

Figure 3.4 demonstrates the gap between the non-farm and construction industry labour productivity up to 2004. The National Institute of Building Sciences (NIBS 2007) has developed a potential forecast in construction productivity in the USA due to BIM. (NIBS 2007) state that the rate of improvement will depend on how seriously the construction industry views the crisis and to provide necessary resources for the adoption of BIM.

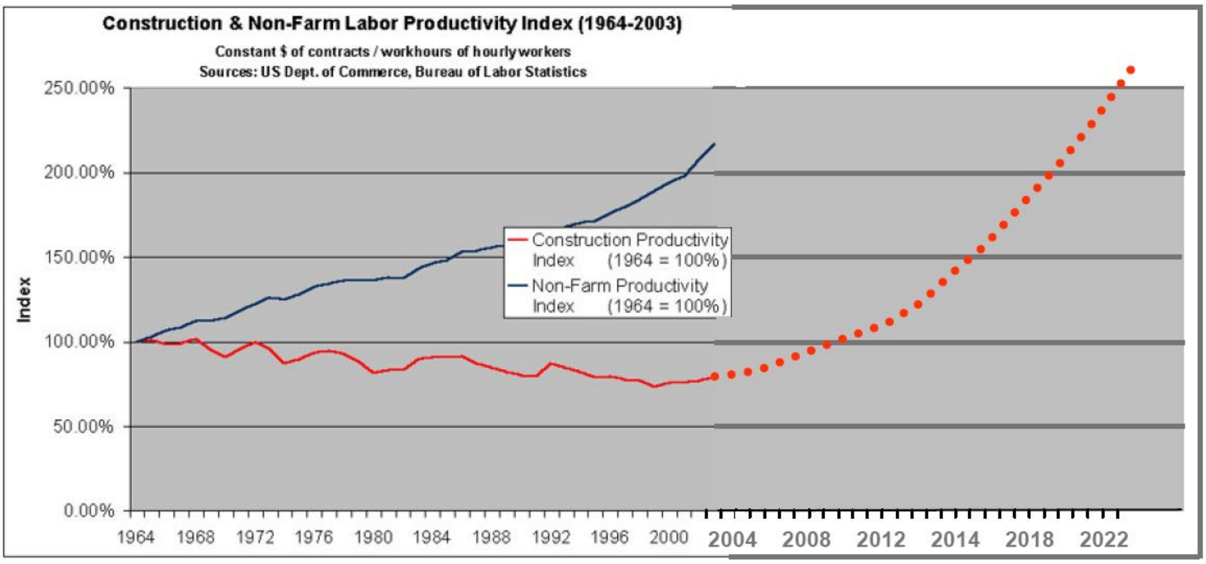


Figure 3.4 –Construction productivity and the future project of productivity through BIM innovation (NIBS 2007)

BIM modelling costs vary based on factors such as the purpose of modelling effort, phase of project design, level of detail required for the model and the number of updates required within the model. Gee (2012) has determined that BIM modelling costs typically range between 0.1% and 0.5% of construction value for commercial projects. Conservative estimates of project cost savings range from 3% to 5% of total construction value (Gee 2012).

McGraw Hill Construction (MHC 2014) has surveyed the architectural, engineering and contracting (AEC) communities in Australia and New Zealand (ANZ), North America and South Korea to assess the perceived financial benefits of BIM (utilising Return on Investment (ROI) as a quantitative measure). It was found by MHC (2014) that 75% of ANZ firms have experienced a positive Return on Investment (ROI) for BIM, with 30% citing a ROI of 25% or more.

Figure 3.5 compares the perceived ROI for BIM in ANZ, North America and South Korea (MHC 2014). It is suggested that ANZ firms may be reporting higher ROI's because they are leveraging learnings from with ANZ to achieve better ROI more quickly than has been typical in North America.

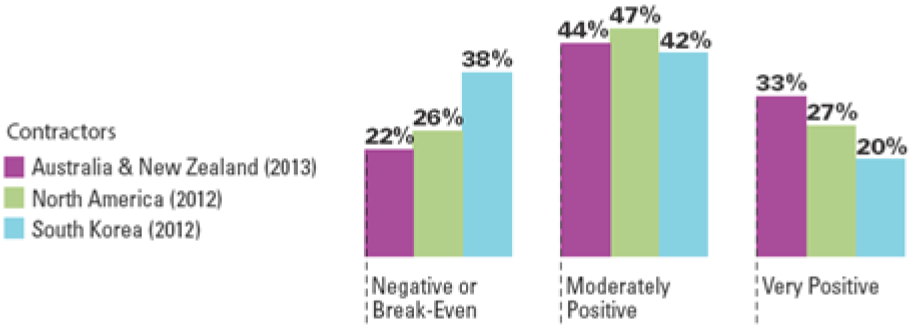


Figure 3.5 –Perception of ROI of BIM by contractors (MHC 2014)

While the construction industry is working on a variety of BIM initiatives to address specific immediate needs, a co-ordinated approach with industry and government collaborating to accelerate adoption of BIM would provide productivity benefits flowing to the entire economy (buildingSMART Australasia 2012).

It is evident that the financial benefits realised by AEC firms would have a flow-on effect throughout the industry and into the wider economy. The adoption of BIM in modern society will assist economies to move towards digitalisation which will contribute to productivity, maintain global competitiveness and improve social wellbeing.

3.3 Environmental Impact

Sustainability has become crucial in the use of resources, greenhouse gas emissions and the state of the fabric of our major urban areas. Energy demand in the building sector accounts for approximately 23% of Australia's total greenhouse gas (buildingSMART Australasia 2012).

The construction industry has traditionally focused on operational and embodied energy of buildings as a way of becoming more sustainable. Alwan and Jones (2014) discuss that an important aspect when calculating a building's carbon footprint is the impact that embodied energy of construction materials can have on the decision making when designing buildings. The significance of embodied carbon becomes greater in "low carbon" buildings as operational carbon is reduced and therefore has a significant impact on the carbon footprint (Iddon & Firth 2013).

Im and Bhandari (2012) discuss that BIM models serve to generate confidence in the use of energy modelling tools and their predicted energy savings for commercial buildings. It is stated that accurate modelling ultimately has an impact on the environment due to increased energy savings, better data to assess financing for retrofits as well as more accurate emissions predictions.

Li et. al. 2012 discuss that computational BIM models can be used to calculate a building's carbon emissions by integrating the system with carbon emission and energy analysis tools. This quantitative calculation method using computational models for the carbon emissions of buildings allows the quantity of material consumption and carbon emissions to be calculated in real time during the whole construction process. This additional quantification of carbon emission during a building's construction stage allows optimisation of the construction plan to assist in the selection of low emission materials (Li et. al. 20112).

McGraw Hill Construction (2014) report that in Australian and New Zealand 53% and 67% of contracting and architectural / engineering firms respectively use BIM to coordinate different building systems to improve building energy performance, 38% and 44% respectively report the use of BIM to create tighter building envelops through BIM-enhanced prefabrication and 33% and 24% report better waste management.

It is evident that the adoption of BIM will foster innovation and the continuous advancement of productivity, efficiency, quality, and sustainability through energy use reduction in building construction and operations, leading to a better built environment for end users, clients, and stakeholders.

4 Technological Management of BIM in Construction

4.1 Management of BIM in Construction

Succar (2013a) discusses that the management of BIM technology is based upon push-pull knowledge transactions occurring within or between BIM fields and sub-fields. Knowledge is transferred to other fields and sub-fields by push mechanisms 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 (Succar 2013a).

Figure 4.1 shows the interactions between fields (horizontal transfer) and between sub-fields (vertical transfer). Figure 4.2 shows a Venn diagram demonstrating the interaction between the policy, process and technology fields for the development of BIM technology.

A summary of a survey undertaken by MacGraw Hill Construction (2014) to identify the push-pull factors that would increase the benefits of BIM for AEC firms is shown in Figure 4.3. It is evident that the integration of BIM data with mobile devices and the development of mobile apps is the most prevalent factor in the continued adoption of BIM technologies during construction.

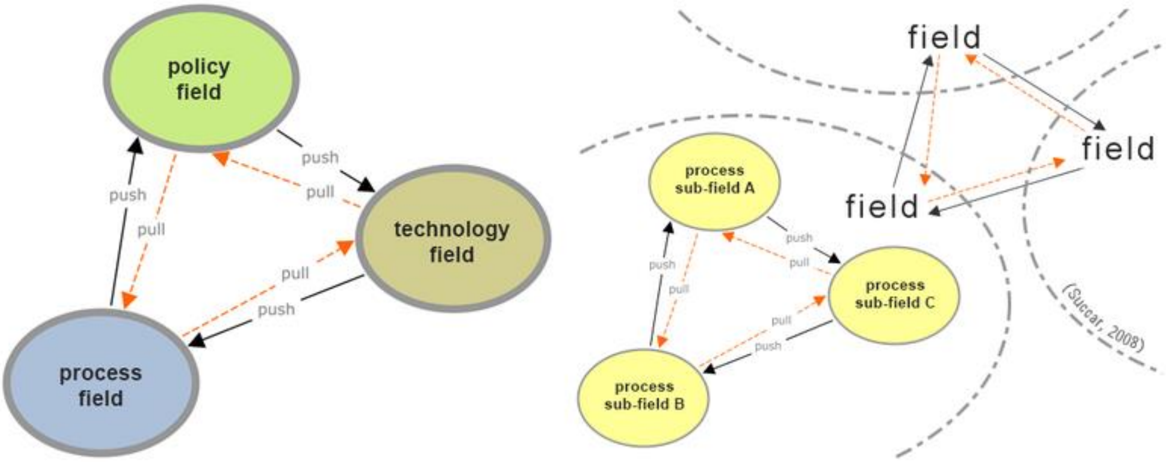


Figure 4.1 – Push-pull technology interactions between BIM fields and sub-fields (Succar 2013a)

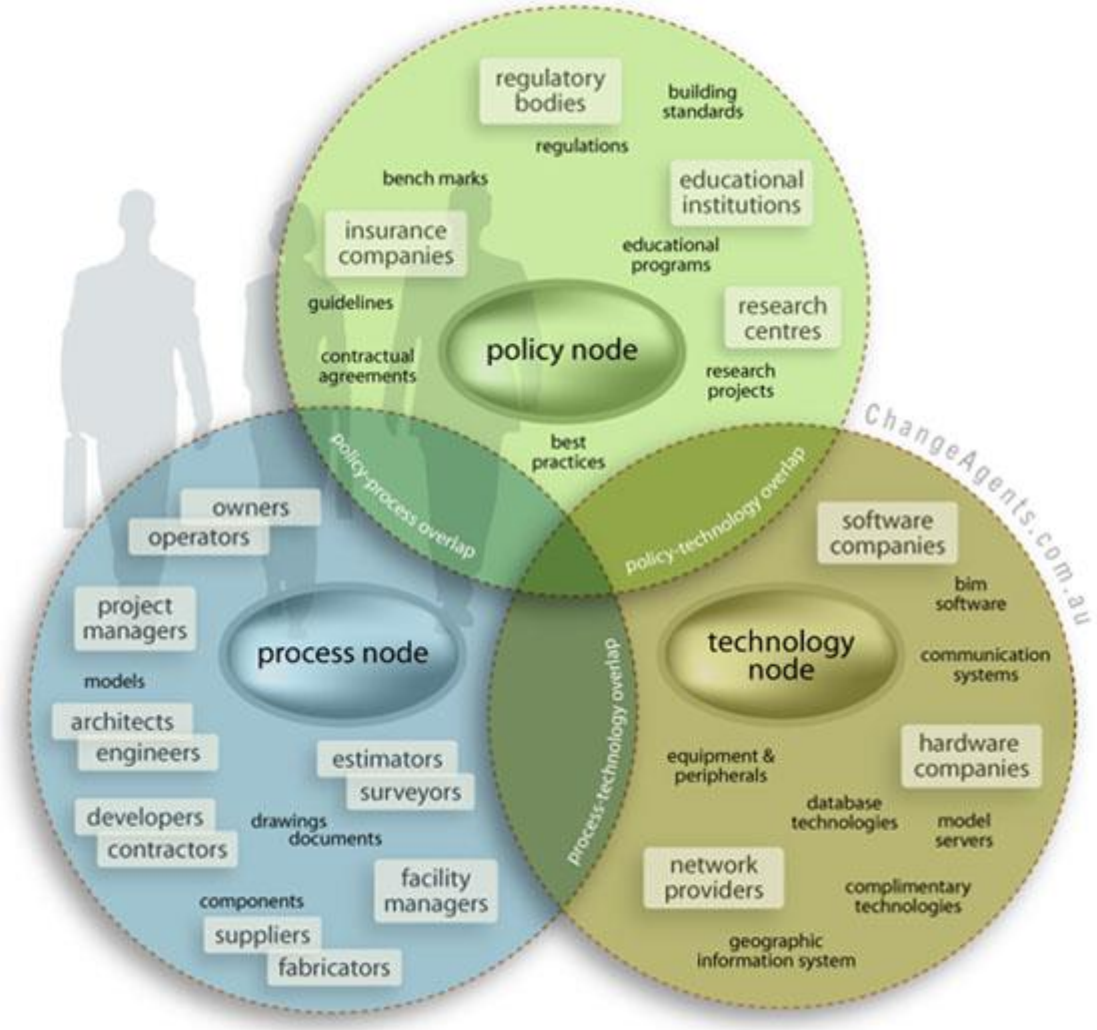


Figure 4.2 – Detailed description of the process, policy and technology nodes in the management of BIM technology, applicable to contractors (Succar 2008a)

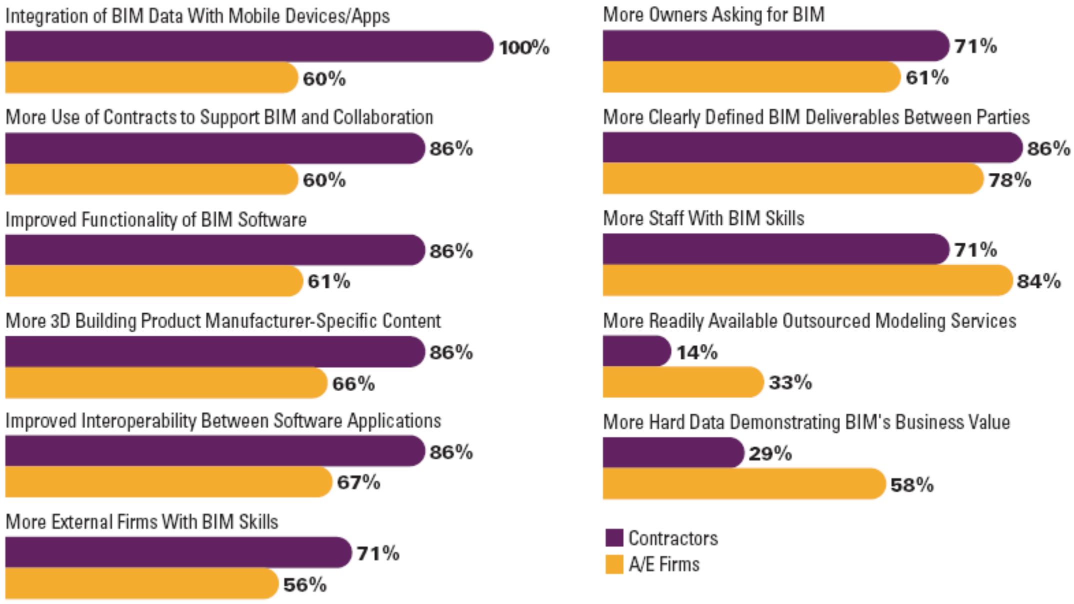


Figure 4.3 – Factors most likely to increase BIM benefits for contractors and architectural/engineering firms (MHC 2014)

This management of technology is consistent with two types of technology transfer (vertical and horizontal) identified by Bennet and Vaidya (2001). Vertical transfer involves progressing from research to development to production and therefore follows the progressive stages of invention, innovation and diffusion, with the technology becoming more commercialised as it proceeds through each stage.

Horizontal transfer involves technology being transferred from one operational environment to another by disseminating the technology and extending its application into other contexts. Horizontal transfer is of concern to companies that wish to maximise the return from their technology but may be unable to do this by direct selling the end products into the market place (Bennet & Vaidya 2001).

In terms of policy, governments are working towards the development of regulations, standards and guidelines. An example is buildingSMART Australasia's (2012) "National Building Information Modelling Initiative" which identifies that the execution of a National BIM Initiative will drive much needed change in the Australian building and construction sector. The policy will significantly contribute toward other Australian Government agendas including preparing for a low carbon future, realising the Government's digital economy strategy, boosting Australia's international competitiveness and enhancing world trade in building and construction services (buildingSMART Australasia 2012).

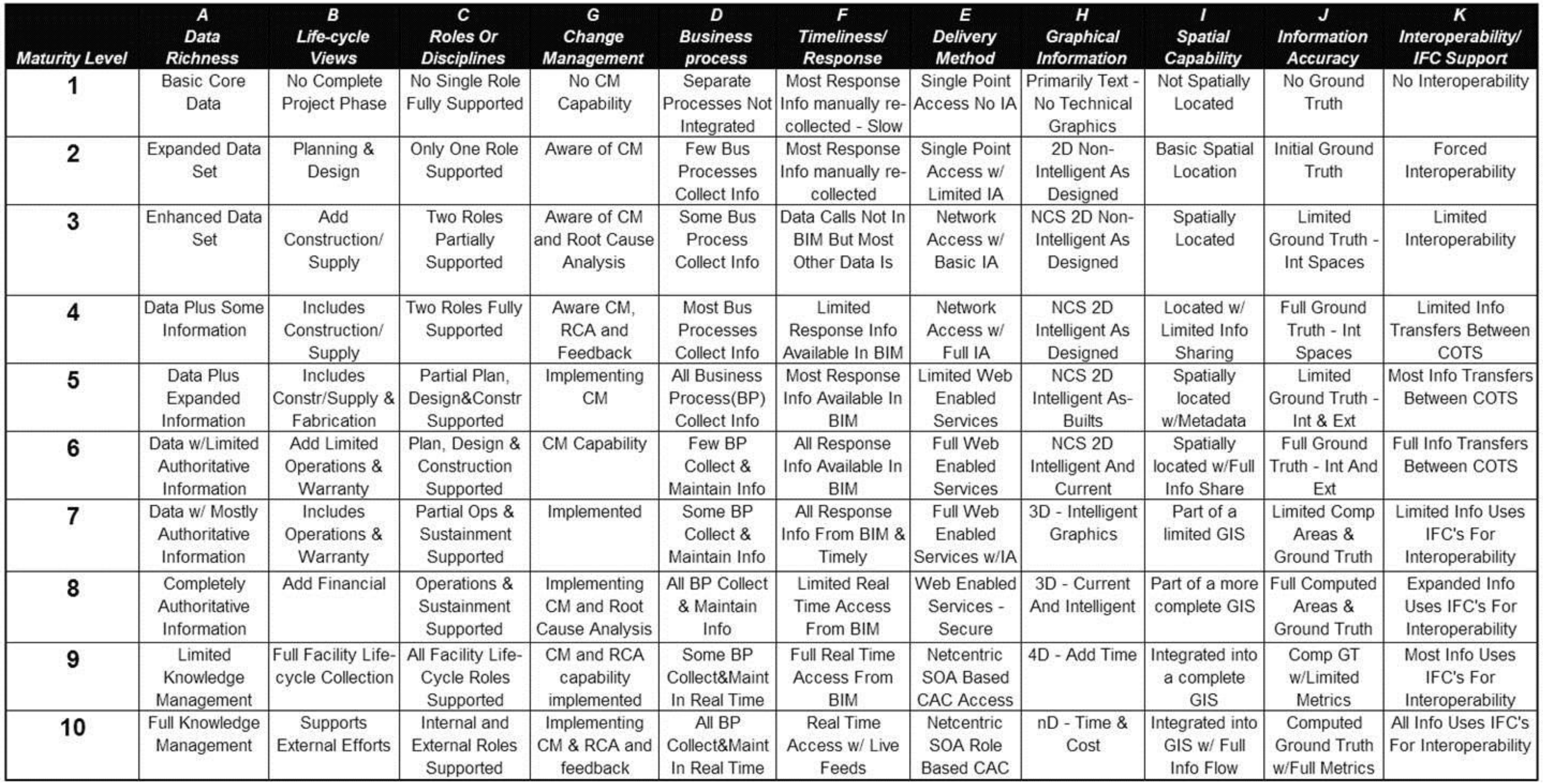
In terms of processes, the National Building Information Model Standard (NBIMS) Capability Maturity Model (CMM) is a tool used for the strategic management of BIM for an organisation (McCuen et. al. 2012). In this standard, the group of stakeholders in the BIM discussion is referred to as the AECO stakeholder model is to meet the future needs of a more streamlined community and build on existing best business practices.

The CMM allows stakeholders to evaluate their business practices along a continuum or spectrum of desired technical levels of functionality (NIBS 2007). The model is defined in Figure 4.4 (NIBS 2007) to allow AECO stakeholders to use the CMM as a tool to determine current BIM maturity to develop organisational goals for the future development of BIM capability.

In terms of technology, Table 4.1 provides an overview of current BIM software providers and their relevant products. It should be noted that this is not an exhaustive list and there is continuous development and integration of existing technologies (for example, CostX is a product that enables take-off quantities from 2D drawings and generation of automatic quantities from BIM).

Based upon the policy, process and technology interfaces, the push-pull exchanges between fields and within sub-fields for construction is shown in Table 4.2.

It is evident that innovation of BIM technologies is a continuous and iterative system consisting of policies, processes and technology. These fields interact through push-pull mechanisms, and it can be seen that case studies, the feedback to technology, training of skilled graduate, development of solutions, hardware and software, government, industry and universities all have a role in the innovation of BIM.



Maturity Level	A Data Richness	B Life-cycle Views	C Roles Or Disciplines	G Change Management	D Business process	F Timeliness/ Response	E Delivery Method	H Graphical Information	I Spatial Capability	J Information Accuracy	K Interoperability/ IFC Support
1	Basic Core Data	No Complete Project Phase	No Single Role Fully Supported	No CM Capability	Separate Processes Not Integrated	Most Response Info manually re-collected - Slow	Single Point Access No IA	Primarily Text - No Technical Graphics	Not Spatially Located	No Ground Truth	No Interoperability
2	Expanded Data Set	Planning & Design	Only One Role Supported	Aware of CM	Few Bus Processes Collect Info	Most Response Info manually re-collected	Single Point Access w/ Limited IA	2D Non-Intelligent As Designed	Basic Spatial Location	Initial Ground Truth	Forced Interoperability
3	Enhanced Data Set	Add Construction/ Supply	Two Roles Partially Supported	Aware of CM and Root Cause Analysis	Some Bus Process Collect Info	Data Calls Not In BIM But Most Other Data Is	Network Access w/ Basic IA	NCS 2D Non-Intelligent As Designed	Spatially Located	Limited Ground Truth - Int Spaces	Limited Interoperability
4	Data Plus Some Information	Includes Construction/ Supply	Two Roles Fully Supported	Aware CM, RCA and Feedback	Most Bus Processes Collect Info	Limited Response Info Available In BIM	Network Access w/ Full IA	NCS 2D Intelligent As Designed	Located w/ Limited Info Sharing	Full Ground Truth - Int Spaces	Limited Info Transfers Between COTS
5	Data Plus Expanded Information	Includes Constr/Supply & Fabrication	Partial Plan, Design&Constr Supported	Implementing CM	All Business Process(BP) Collect Info	Most Response Info Available In BIM	Limited Web Enabled Services	NCS 2D Intelligent As-Builts	Spatially located w/Metadata	Limited Ground Truth - Int & Ext	Most Info Transfers Between COTS
6	Data w/Limited Authoritative Information	Add Limited Operations & Warranty	Plan, Design & Construction Supported	CM Capability	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	Implemented	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	Implementing CM and Root Cause Analysis	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	CM and RCA capability implemented	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	Implementing CM & RCA and feedback	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

Figure 4.4 – Capability maturity model (NIBS 2007)

Table 4.1 – Current BIM software providers and relevant products (adapted: Gee 2012)

Software Provider	Software Name (Capabilities)
Autodesk	▪ Revit Architecture (design authoring) ▪ Revit Structure (design authoring) ▪ Revit MEP (design authoring) ▪ Ecotect (daylighting and energy analysis) ▪ NavisWorks Manage (clash detection/3D coordination) ▪ NavisWorks Freedom (free model viewer)
Bentley	▪ Microstation TriForma (design authoring)
Google	▪ Google Sketchup (modeling software (no parametric data))
Solibri	▪ Solibri Model Checker BIM (model validation software)
Synchro	▪ Synchro 4D (4D scheduling software)
Tekla	▪ Tekla Structures (design authoring) ▪ Tekla Construction ▪ Tekla BIMsight (clash detection/3D coordination)
Vico	▪ Vico Office (5D model based estimating)

Table 4.2 – Push-pull interactions between policy, process and technology for construction and contractors (adapted: Succar 2013a)

Push-Pull Direction	Process, Policy and Technology Node Interactions		
	Policy	Process	Technology
Push into other fields	Push into “Process” ▪ Skilled graduates ▪ New standards ▪ New guidelines Push into “Technology” ▪ Concepts ▪ Taxonomy	Push into “Policy” ▪ Case studies Push into “Technology” ▪ Feedback to technology	Push into “Policy” ▪ Innovative solutions and new equipment Push into “Process” ▪ Innovative solutions and new equipment
Pull from other fields	Pull from “Process” ▪ Subject matter experts Pull from “Technology” ▪ Interoperability	Pull from Policy ▪ Skilled graduates ▪ New standards ▪ New guidelines Pull from “Technology” ▪ Development of solutions	Pull from “Policy” ▪ Standardisation efforts Pull from “Process” ▪ Requirements and experience
Push-Pull within the same field	Push-pull interchanges between ▪ Research & universities ▪ Architects and engineers	Push-pull interchanges between ▪ Requests for information from designers ▪ Owners contractual requirements	Push-pull interchanges between ▪ Hardware ▪ Software

4.2 Effectiveness of BIM Management in Construction

Ikerd (2008) has identified that the adoption of BIM has followed the classic adoption life cycle model of new technology with innovators and early adopters leading the industry for BIM implementation. This is then followed by the early and late majority of adopters and finally the “resistance” (sceptics of the new technology). Figure 4.5 demonstrates the adoption life cycle with the “chasm” representing the initial challenges of change (Ikerd 2008).

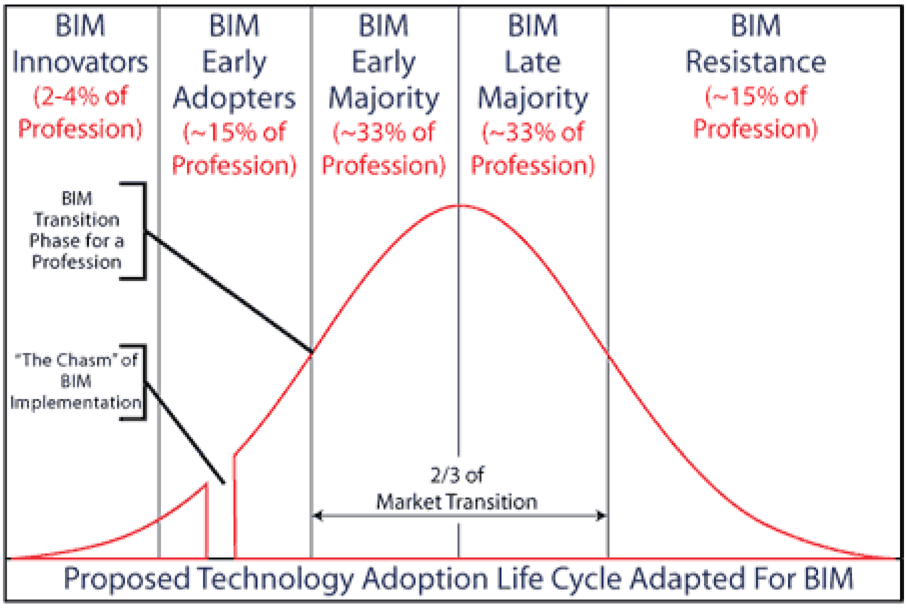


Figure 4.5 – Adoption life cycle model of BIM technology

Figure 4.6 demonstrates that expected value of improvements throughout the asset life cycle where it can be seen that owners / operators and contractors are likely to receive the most benefits.

Succar (2010) explores the relationship between the two variables “BIM leadership” and expected “BIM benefits” regarding AECO stakeholders. This is demonstrated in Figure 4.7 where AECO stakeholders are clustered around their respective life cycle phases “design (D)”, “construction (C)” and “operation (O)”.

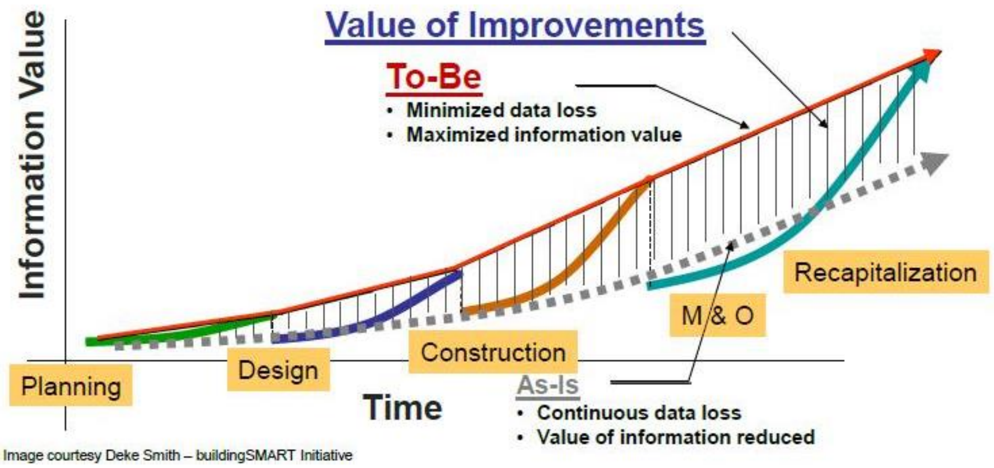


Figure 4.6 – Expected value of improvements due to BIM throughout the asset life cycle (Cholakis 2012)

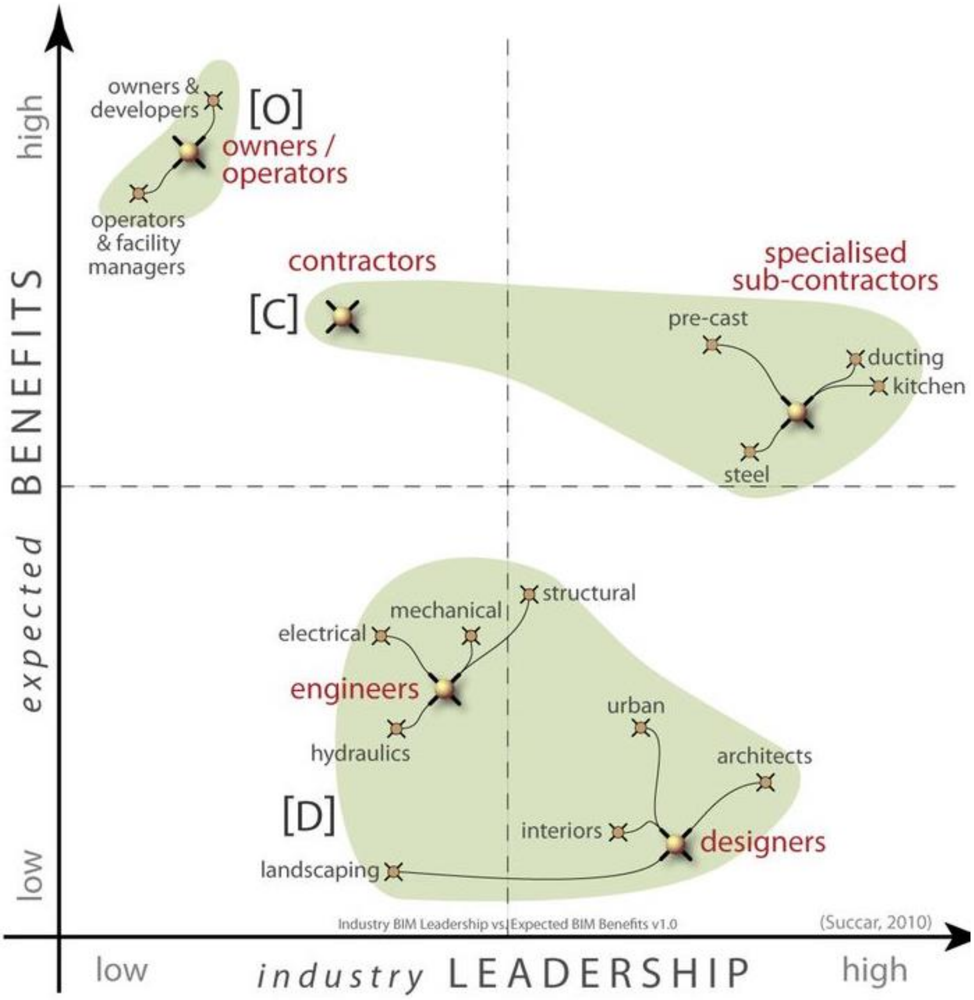


Figure 4.7 – BIM industry leadership versus expected benefits (Succar 2010)

Succar (2010) discusses that it is intriguing that it appears those who stand to benefit the most (owners and contractors) are not the same as those who are actually leading the pack. Deutsch (2012) states that the effectiveness of BIM management is consistent with Gartner's Hype Cycle that new technologies generally follow, as shown in Figure 4.8.

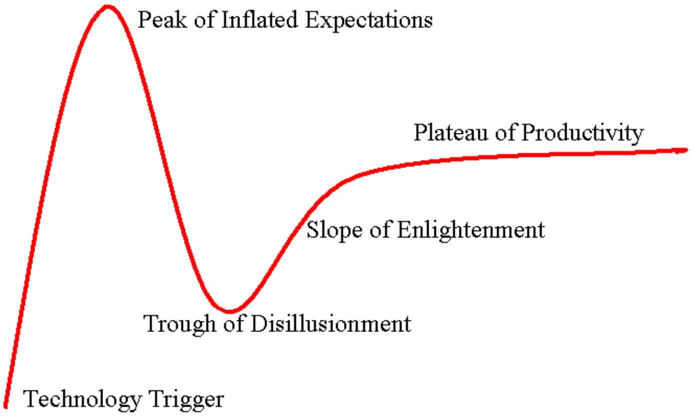


Figure 4.8 – Gartner Hype Cycle (Deutsch 2012)

While it is acknowledged that BIM encourages construction stakeholders to apply to overcome construction project problems such as delay, clash of design by different professionals and construction cost overrun (Latiffi et. al. 2013) as well as improve communication and collaboration between stakeholders, Deutsch (2012) suggests that BIM is currently in the "trough of disillusionment", which is caused by inflated expectations that are not met.

Ikerd (2008) discusses that BIM technology has the potential to rapidly grow due to the "early majority" and "late majority" as shown on the S-curve of technological progress in Figure 4.9. It is demonstrated that this growth is initially led by architectural and then engineering firms ("early adopters"), followed by contractors and sub-contractors and then owners / operators.

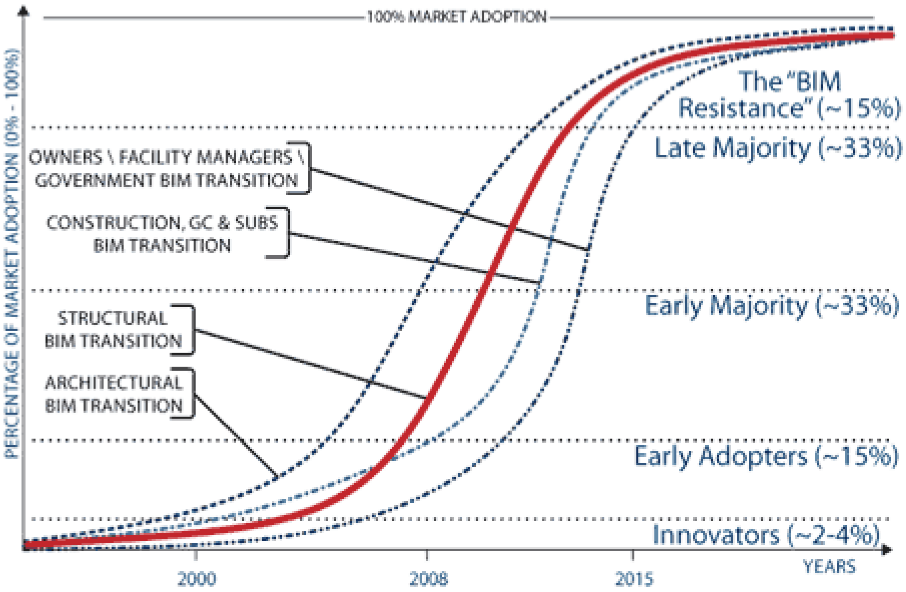


Figure 4.9 – Rapid adoption of BIM technology by industry type (Deutsch 2012)

Xu et. al. (2014) undertook research to examine the factors that influence the adoption of BIM. The model drew upon technology acceptance models and innovation diffusion theory. The findings demonstrate that attitude, technological, and organisational dimensions indirectly affect the actual use of BIM through perceived usefulness (PU) and perceived ease of use (PEU), with PU and PEU being the primary determinants of BIM adoption. A striking finding was the positive influence of the attitude dimension on the actual adoption and use of BIM.

It is evident that the early adopters and current leaders of BIM are the least to benefit from the technology. It appears that there would be significant benefits in a shift towards owners / operators and contractors taking an active role in BIM leadership and developing an industry specific framework to bring the AECO stakeholders into alignment with the architectural and engineering firms that are currently leading process improvement approaches.

5 Future of BIM Technology

5.1 Future of BIM Technology

The Government Construction Client Group (GCCG 2011) in the UK is an example of government forming policy. The GCCG is working towards design, modelling and data exchange for BIM processes in the immediate past, current and future to deliver clear guidance to the UK industry. This involves utilising a set of maturity levels, similar to those defined by Succar (2008b) in Figure 5.1. Each of the stages (pre-BIM, stage 1, stage 2 and stage 3) can be subdivided into sequential steps. “Stages” are defined as radical changes while BIM steps are incremental ones within the stages (Succar 2008b).

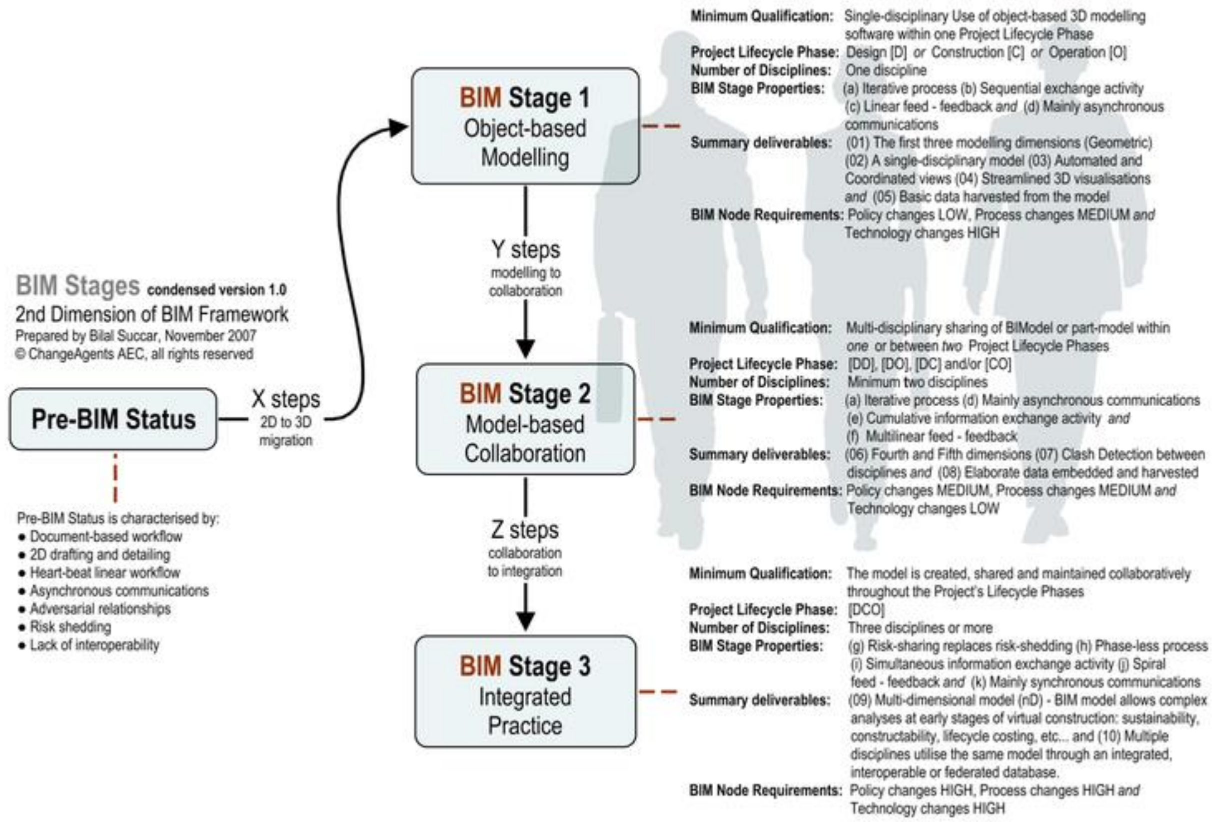


Figure 5.1 – Stages of BIIM (Succar 2008b)

The GCCG (2011) has developed a road map to outline the necessary guidelines, regulations, liability protection and educational programs necessary for systematic progress. This involves standardising and defining “object libraries” and “process and data management” as well as developing “guiding documents”. The UK’s model 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 as per Figure 5.2 (GCCG 2011).

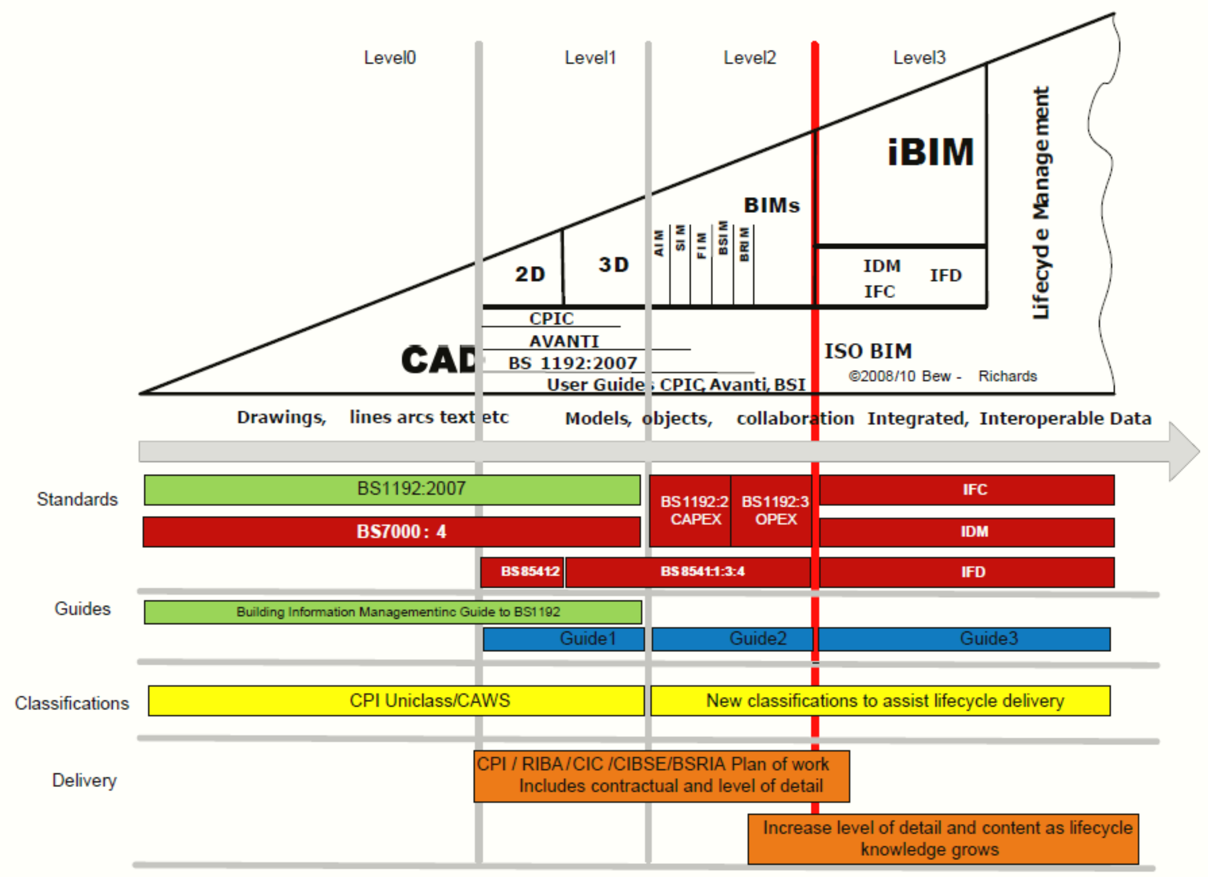


Figure 5.2 – UK government's BIM road map (GCCG 2011)

In a similar manner, the scope of the "National BIM Standard-United States" is built around the concept of ever-increasing levels of importance, with International Standards at the centre (NIBS 2007). Figure 5.3 demonstrates the hierarchy of global standards, with the International Standards Organisation (ISO) being the fully vetted standards having the highest level of criticality and acceptance. Draft International Standards (DIS) are next in the hierarchy followed by Publically Available Standards (PAS) third. Figure 5.4 demonstrates the process towards the development process for standards (Cerovsek 2011).

Figure 5.3 – Hierarchy of Standards (NIBS 2007)

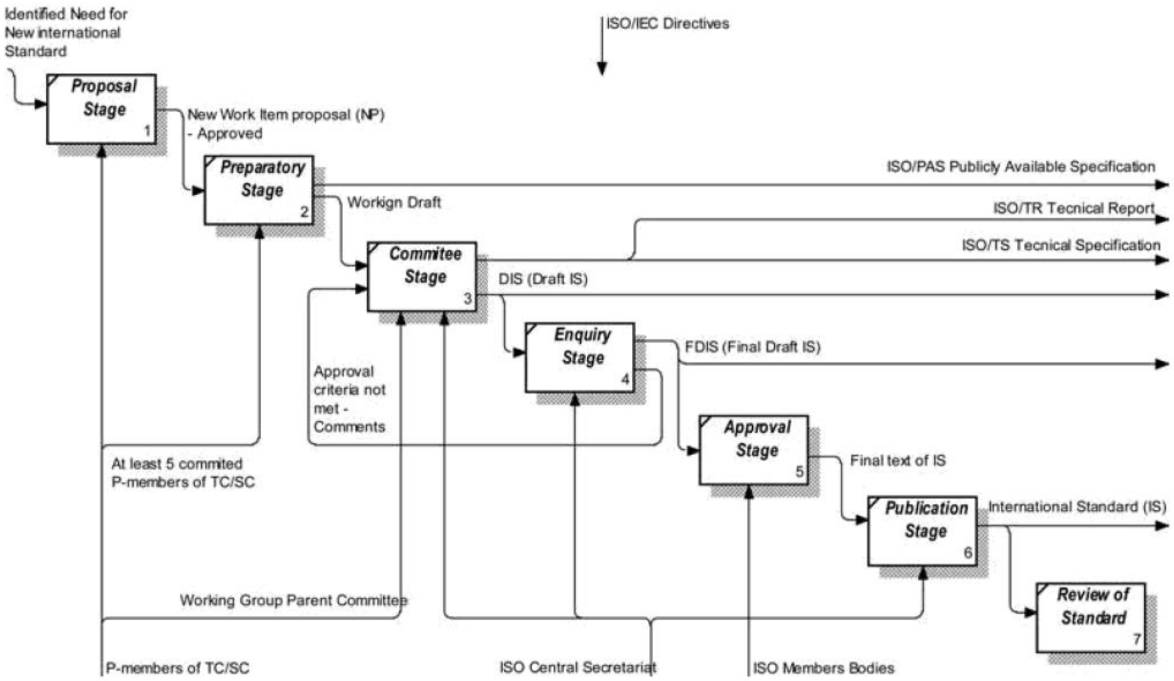


Figure 5.4 – Hierarchy of Standards (Cervosek 2011)

Succar (2013b) has developed a conceptual model to demonstrate the multi-dimensional relationship between the three main components of the BIM framework. The framework is comprised of “BIM stages” (capability benchmarks as per Figure 5.1), “BIM fields” (stakeholders requirements and deliverables) and “BIM lenses” (depth and breadth of enquiry necessary to identify, assess and qualify BIM fields and BIM stages).

Cerovsek (2011) has developed a “BIM cube” framework that is proposed to provide guidelines for research in BIM project communication within three life cycles, namely the building project life cycle, BIM technologies life cycle and BIM model life cycle. The interaction between these “faces” of the BIM cube are demonstrated in Figure 5.5.

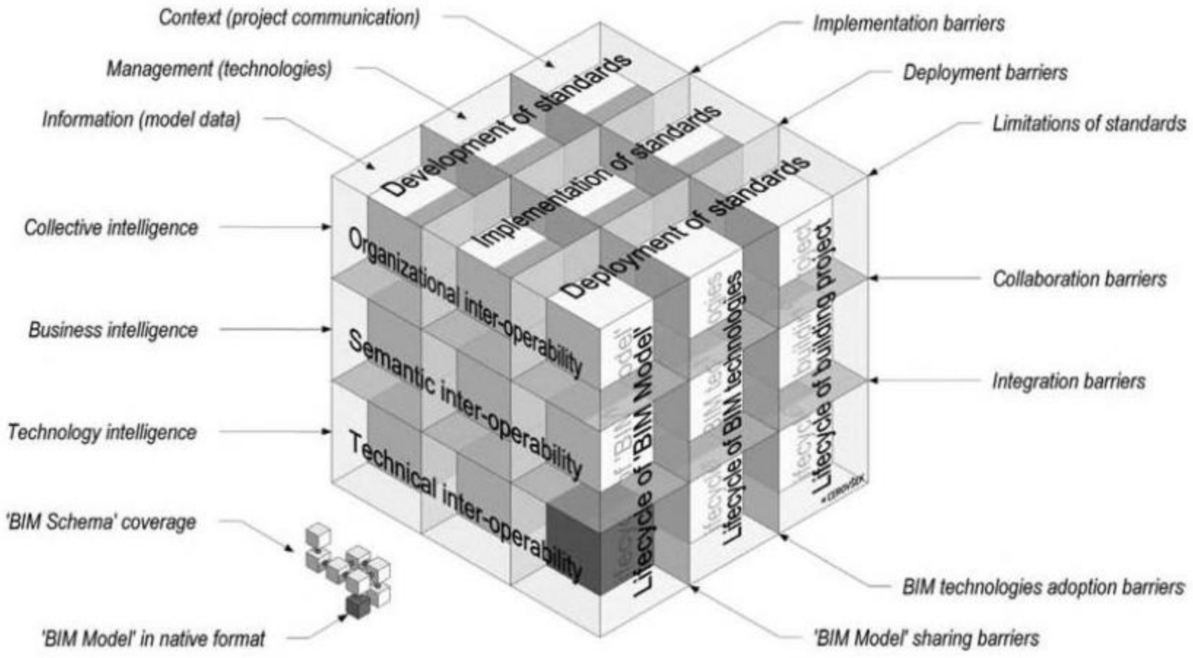


Figure 5.5 – Proposed BIM cube framework (Cerovsek 2011)

In Australia, buildingSMART Australasia (2012) has proposed a range of joint collaborative initiatives for government and industry to move towards the wider adoption and development of BIM, including:

- Requiring BIM for Australian Government procurement for built environment projects;
- Encouraging State and Territory Governments and the private sector to require BIM for procurement for built environment projects;
- Developing Australian BIM contracts for adoption;
- Developing Australian technical codes and standards for BIM;
- Aligning Australian BIM codes and standards with international equivalents;
- Developing and delivering a BIM awareness and promotion program for key government and broader industry participants;
- Developing and starting delivery of BIM training packages to industry practitioners;
- Encouraging the inclusion of BIM as a collaborative technology for both professional education and vocational training in the tertiary sector;
- Enabling progressive access to an Australian library of generic BIM objects and information for manufactured products that comply with Australian BIM standards;
- Developing industry protocols for information exchange to underpin BIM and collaborative practice;
- Coordinating activity between relevant sectors of the Australian economy to enable integrated access to land, geospatial and building information;
- Developing a model-based building regulatory compliance process demonstrator; and
- Developing an implementation plan for the transition of Australian regulatory codes and compliance mechanisms to model-based performance based systems.

As industry continues to collaborate and “capability and maturity” models are developed and refined for AECO stakeholders, new and/or improved processes through well defined, measurable and monitored BIM phases (or stages or versions) will ultimately take account of all the three components of technology, processes and policy. It is evident that there is an increasing focus on developing an international standard and guidelines for the management of BIM.

The improved exchange of information using BIM-based technologies will support integrated design and delivery solutions in the future. The importance of developing and delivering BIM awareness and promoting the technology has been identified. Various governments around the world are taking leadership with the implementation of BIM technologies by adopting policies in favour BIM of adoption.

5.2 Future of BIM in the Construction Industry

McGraw Hill Construction (2014) state that the ability of contractors to bring the value of BIM to the field is one of the big trends occurring worldwide. The rapid development of geo-referenced information has changed the data is accessed an interlinked and smartphones have been identified as the main enablers of this change (Olbrich et. al. 2013).

It is reported that in ANZ, 54% of contractors utilising BIM are using wireless handheld devices to make models available to workers on site with 50% of contractors utilising the traditional PC in the on-site trailer (MHC 2014). A rising technology in the context of handheld devices is augmented reality. Augmented reality fuses the real world captured with the smartphone camera with geo-referenced data (Olbrich et. al. 2013). Yeh et. al. (2012) have developed a wearable device coined the iHelmet that consists of a construction helmet, an iPod Touch, and an Optoma light-emitting diode (LED) projector. Field studies indicate that the mean completion time to find relevant information was significantly reduced for participants using the iHelmet (44 seconds) than traditional hard-copy drawings (99 seconds). The mean success rates of participants arriving at the correct answers were significantly improved for the iHelmet (91.6%) versus the traditional approach (64.3%).

It is anticipated that future iterations of augmented reality will be used to capture on-site information to significantly increase the accuracy of data-capture and increase the efficiency of obtaining, storing and retrieving construction information (Olbrich et. al. 2013). Challenges identified with the development of these systems is the requirement for stakeholders involved in the overall building lifecycle to have mobile access to the management system within on-site inspections and to automate feedback of newly generated information into the BIM (Olbrich et. al. 2013).

Accurate and frequent construction progress tracking provides critical input data for project systems such as cost, schedule control, and billing (Turkan et. al. 2013). McGraw Hill Construction (2014) states that 50% of contractors report that BIM would be useful to allow model-driven layouts on-site, 44% would use BIM for reporting on the status/progress of works and 40% would provide model-driven prefabrication requirements to sub-contractors (40%) (MHC 2014).

Turkan et. al. (2013) discuss that conventional progress tracking is labour intensive, often driven by arcane rules and sometimes subject to negotiation, however automated and object oriented recognition systems that convert each object to its earned value are in development. Due to the limitations with traditional approaches, Turkan et. al. (2013) are currently refocusing future research onto automated earned value tracking. It is anticipated that this will substantially improve the accuracy of progress tracking and therefore provide better support to project systems such as billing.

It has been identified that 59% of contractors indicate that BIM would be useful to prepare the final “As-Built” model for the owner / operator (MHC 2014). Most data is traditionally collected manually and it has been found that errors are often introduced during data collection, pre-processing, and modelling. Anil et. al. (2013) has developed a method of generating 3D “As-Built” models that provides a 40% reduction in time to collect relevant data and is capable of identifying almost six times more errors compared to the traditional physical measurement methods.

As attitudes towards BIM change there will be a wider acceptance and adoption of BIM technology by contractors during construction. Attempts to improve progress tracking have recently focused on automation, using technologies such as 3D imaging, global positioning systems, ultra wide band indoor locating, handheld computers, voice recognition, wireless networks, and other technologies in various combinations.

It is envisaged that wearable augmented reality devices will alleviate the requirement to carry bulky construction drawings and reports to the site as well as reduce the effort required to obtain, store and retrieve construction data. It is also envisaged that other technologies currently used in project management systems will be incorporated with BIM technologies. In the future, “As-Built” models will be delivered to owners / operators from point cloud data collected by laser scanners.

6 Conclusions

BIM is a 3D digital representation of a building founded on open standards for interoperability and through its comprehension of spatial relationships. The conceptual underpinnings of BIM were identified as early as 1962 and previous evolutions of BIM have been the development of CAD technologies. By the year 2000, software was developed which made object oriented programming possible and the latest technologies allow the addition of time attributes to components to allow generation of construction schedules.

Discipline-specific knowledge and tracking of changes are captured in single as it is passed between AECO stakeholders. This has resulted in shifts in the social interaction as well as roles and responsibilities of the contractors involved in with BIM. A significant proportion of construction firms have recognised that BIM enhances a contractor's reputation as an industry leader.

It is evident that BIM technology has a substantial a positive impact on modern society by increasing design and construction efficiency, as well as providing a safer work environment for construction workers. It can be seen that the use of BIM in safety in design has the potential to increase the safety of buildings throughout a building's entire life cycle.

It is evident that the financial benefits realised by AEC firms would have a flow-on effect throughout the industry and into the wider economy. The adoption of BIM in modern society will assist economies to move towards digitalisation which will contribute to productivity, maintain global competitiveness and improve social wellbeing.

It is evident that the adoption of BIM will foster innovation and the continuous advancement of productivity, efficiency, quality, and sustainability through energy use reduction in building construction and operations, leading to a better built environment for end users, clients, and stakeholders.

It is evident that innovation of BIM technologies is a continuous and iterative system consisting of policies, processes and technology. These fields interact through push-pull mechanisms, and it can be seen that case studies, the feedback to technology, training of skilled graduate, development of solutions, hardware and software, government, industry and universities all have a role in the innovation of BIM.

It is evident that the early adopters and current leaders of BIM are the least to benefit from the technology. It appears that there would be significant benefits in a shift towards owners / operators and contractors taking an active role in BIM leadership and developing an industry specific framework to bring the AECO stakeholders into alignment with the architectural and engineering firms that are currently leading process improvement approaches.

As industry continues to collaborate and "capability and maturity" models are developed and refined for AECO stakeholders, new and/or improved processes through well defined, measurable and monitored BIM phases (or stages or versions) will ultimately take account of all the three components of technology, processes and policy. It is evident that there is an increasing focus on developing an international standard and guidelines for the management of BIM.

The improved exchange of information using BIM-based technologies will support integrated design and delivery solutions in the future. The importance of developing and delivering BIM awareness and promoting the technology has been identified. Various governments around the world are taking leadership with the implementation of BIM technologies by adopting policies in favour of BIM adoption.

As attitudes towards BIM change there will be a wider acceptance and adoption of BIM technology by contractors during construction. Attempts to improve progress tracking have recently focused on automation, using technologies such as 3D imaging, global positioning systems, ultra wide band indoor locating, handheld computers, voice recognition, wireless networks, and other technologies in various combinations.

It is envisaged that wearable augmented reality devices will alleviate the requirement to carry bulky construction drawings and reports to the site as well as reduce the effort required to obtain, store and retrieve construction data. It is also envisaged that other technologies currently used in project management systems will be incorporated with BIM technologies. In the future, “As-Built” models will be delivered to owners / operators from point cloud data collected by laser scanners.

7 Recommendations

Based on the conclusions of this report, it is recommended that:

- Construction contractors incorporate BIM in the design of site layouts, construction workflows and use BIM to collaborate on projects;
- Laser scanning technologies are combined with BIM to provide 3D “As-Built” models to owners / operators;
- Additional research is undertaken into combining augmented reality with BIM;
- Industry continues to develop and refine capability and maturity models for AECO stakeholders;
- Relevant world-wide BIM codes and standards are aligned to provide an internationally consistent approach to BIM;
- Owners / operators are educated on the benefits of BIM to increase the demand for BIM services; and
- Governments are encouraged to require full collaborative BIM as a legal requirement for their building procurements.

List of References

Alwan, Z & Jones, P 2014, 'The importance of embodied energy in carbon footprint assessment', *Structural Survey*, vol. 32, no. 1, pp. 49-60.

Anil, EB, Tang, P, Akinci, B & Huber, D 2013, 'Deviation analysis method for the assessment of the quality of the as-is Building Information Models generated from point cloud data', *Automation in Construction*, vol. 35, pp. 507-16.

Avramides, M 2012, 'The Battle for Innovation: A Reverse Strategy', *ENR: Engineering News-Record*, vol. 268.

Bennett, D & Vaidya, K 2001, 'Meeting Technology Needs of Enterprises for National Competitiveness', in Management of Technology, Vienna Global Forum: *proceedings of the Management of Technology, Vienna Global Forum* United Nations Industrial Development Organization, Vienna, Austria.

buildingSMART Australasia 2012, *National Building Information Modelling Initiative. Vol.1, Strategy: A strategy for the focussed adoption of building information modelling and related digital technologies and processes for the Australian built environment sector*, Department of Industry, Innovation, Science, Research and Tertiary Education, Sydney.

Cervosek, T 2011, 'A review and outlook for a "Building Information Model" (BIM): a multi-standpoint framework for technological development', *Advanced Engineering Informatics*, vol. 25, no. 2, pp. 224-44.

Cholakis, P, 2012, 'What is BIM – Strategy, Process, or Technology?', *Efficient Construction Project Delivery Methods – Sustainability – 3D, 4D, 5D BIM – IPD, JOC, SABER, IDIQ, SATOC, MATOC, MACC, POCA ..* <https://buildinginformationmanagement.wordpress.com/tag/definition-of-bim/>.

Deutsch, R, 2012, 'The State of IPD and BIM: an Owner’s Perspective', *BIM + Integrated Design*, <http://bimandintegrateddesign.com/the-book-2/>.

Engelbart, D 1962, *SRI Summary Report AFOSR-3223, Augmenting Human Intellect: A Conceptual Framework, Prepared*, Director of Information Sciences, Air Force Office of Scientific Research, California.

Gee, J 2012, *Building Information Modeling (BIM), APPA Facilities Institute, Course 466*, APPA Facilities Institute, USA.

Government Construction Client Group (GCCG) 2011, *Building Information Modelling (BIM) Working Party Strategy Paper*, UK Government Construction Client Group, UK.

Hergunsel, M 2011, 'Benefits of Building Information Modeling for Construction Managers and BIM Based Scheduling', Worcester Polytechnic Institute, Worcester.

Hjelseth, E 2010, 'Exchange of Relevant Information in BIM Objects Defined by the Role- and Life-Cycle Information Model', *Architectural Engineering & Design Management*, vol. 6, no. 4, pp. 279-87.

Iddon, CR & Firth, SK 2013, 'Embodied and operational energy for new-build housing: A case study of construction methods in the UK', *Energy & Buildings*, vol. 67, pp. 479-88.

Ikerd, W 2008, 'The Importance of BIM in Structural Engineering, the Greatest Change in Over a Century', *STRUCTURE Magazine*, vol. October 2008.

Im, P & Bhandari, M 2012, 'Use of Flexible Research Platforms (FRP) for BIM and Energy Modeling Research', *ASHRAE Transactions*, vol. 118, no. 2, pp. 197-204, EBSCOhost.

Latiffi, A, Mohd, S, Kasim, N & Fathi, M 2013, 'Building Information Modeling (BIM) Application in Malaysian Construction Industry', *International Journal of Construction Engineering and Management*, vol. 2, no. 4A.

Li, B, Fu, FF, Zhong, H & Luo, HB 2012, 'Research on the computational model for carbon emissions in building construction stage based on BIM', *Structural Survey*, vol. 30, no. 5, pp. 411-25.

McCuen, TL, Suermann, PC & Krogulecki, MJ 2012, 'Evaluating Award-Winning BIM Projects Using the National Building Information Model Standard Capability Maturity Model', *Journal of Management in Engineering*, vol. 28, no. 2, pp. 224-30.

McGraw Hill Construction (MHC) 2014, *The Business Value of BIM in Australia and New Zealand: How Building Information Modeling is Transforming the Design and Construction Industry*, Australia.

Melzner, J, Zhang, S, Teizer, J, Holldermann, S & Bargstadt, H 2012, 'Safety planning based on an object-oriented building model', in European Group for Intelligent Computing in Engineering: *proceedings of theEuropean Group for Intelligent Computing in Engineering*, P Borrmann, et al. (eds.), Herrsching, Germany.

National Institute of Building Sciences (NIBS) 2007, *National Building Information Modeling Standard, Version 1 - Part 1: Overview, Principles, and Methodologies*, National Institute of Building Sciences, USA.

Olbrich, M, Graf, H, Kahn, S, Engelke, T, Keil, J, Riess, P, Webel, S, Bockholt, U & Picinbono, G 2013, 'Augmented reality supporting user-centric building information management', *Visual Computer*, vol. 29, no. 10, pp. 1093-105.

Penttila, H 2008, *The Evolution of BIM Building Information Modelling*, Helsinki University of Technology, Finland,<http://www.mittaviiva.fi/hannu/studies/bim_evo.html>.

Quirk, V 2012, *A Brief History of BIM / Michael S. Bergin*, ArchDaily, viewed 20 April 2014, <http://www.archdaily.com/302490/a-brief-history-of-bim/>.

Sears, A & Jacko, J 2007, *The Human-Computer Interaction Handbook: Fundamentals, Evolving Technologies and Emerging Applications*, 2 edn, CRC Press, NY.

Skandhakumar, N, Reid, J, Dawson, E, Drogemuller, R & Salim, F 2012, 'An Authorization Framework using Building Information Models', *Computer Journal*, vol. 55, no. 10, pp. 1244-64.

Steel, J, Drogemuller, R & Toth, B 2012, 'Model interoperability in building information modelling', *Software & Systems Modeling*, vol. 11, no. 1, pp. 99-109.

Succar, B, 2008a, 'BIM and the Process Improvement Movement', *BIM ThinkSpace*, <http://www.bimthinkspace.com/2008/05/bim-and-the-pro.html#more>.

Succar, B, 2008b, 'Episode 8: Understanding BIM Stages', *BIM ThinkSpace*, <http://www.bimthinkspace.com/2008/02/the-bim-episode.html#more>.

Succar, B, 2010, 'Episode 14: Industry Leadership vs. BIM Benefits', *BIM ThinkSpace*, <http://www.bimthinkspace.com/2010/09/industry-leadership-vs-bim-benefits.html>.

Succar, B, 2013a, 'Field Interactions', *BIM Framework*, <http://www.bimframework.info/2013/12/field-interactions.html>.

Succar, B, 2013b, 'The Tri-Axial Model', *BIM Framework*, <http://www.bimframework.info/2013/12/tri-axial.html>.

Turkan, Y, Bosché, F, Haas, CT & Haas, R 2013, 'Toward Automated Earned Value Tracking Using 3D Imaging Tools', *Journal of Construction Engineering & Management*, vol. 139, no. 4, pp. 423-33.

Wang, L & Leite, F 2012, 'Toward Process-aware Building Information Modeling for Dynamic Design and Management of Construction Processes', in European Group for Intelligent Computing in Engineering: *proceedings of theEuropean Group for Intelligent Computing in Engineering*, P Borrmann, et al. (eds.), Herrsching, Germany.

Xu, H, Feng, J & Li, S 2014, 'Users-orientated evaluation of building information model in the Chinese construction industry', *Automation in Construction*, vol. 39, pp. 32-46.

Yeh, K-C, Tsai, M-H & Kang, S-C 2012, 'On-Site Building Information Retrieval by Using Projection-Based Augmented Reality', *Journal of Computing in Civil Engineering*, vol. 26, no. 3, pp. 342-55.

Zhang, S, Teizer, J, Lee, J-K, Eastman, CM & Venugopal, M 2013, 'Building Information Modeling (BIM) and Safety: Automatic Safety Checking of Construction Models and Schedules', *Automation in Construction*, vol. 29, pp. 183-95.