Investigating the Effectiveness of BIM-BMS Integration on Managing Existing Building Facilities: A New Zealand Educational Building Case

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Attestation of Authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

Signed ______________________________ Date___________01/08/2019_________

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Abstract

Nowadays, the building sector and people's activities in buildings account for nearly 60% of the world's electricity consumption. Wherein, the operation accounts for 87% of total costs in the whole building lifecycle. Hence, it is most efficient in enhancing the sustainable performance in this phase. However, the current information management process in building facilities O&M phase is weak. Towards this problem, a solution of proposing BIM-BMS integration was raised from the literature. Besides, the educational building was identified as the most suitable building type in New Zealand to test. In this regard, the research aims to investigate the effectiveness of BIM-BMS integration in managing existing educational building facilities in New Zealand.

Due to the solution belonging to a complex system, this study adopts a complexity theory. Considering this, a conceptual framework of nD BIM-IKBMS was given. In terms of this, a mixed methods approach was adopted for this study in order to meet the objectives of the study. It is comprising of five stages of data collection: a documentation analysis was made to define the BIM related terminologies in a New Zealand context. Then a focus group interview was conducted to obtain New Zealand specific barriers coupled with specific suggestions. Based on the specific suggestions, a functional framework for the solution was developed and verified on its interoperability and flexibility. Under this framework, a process model was established, which was then adopted to develop a working prototype. Once the working prototype was deployed in a pilot case, a thermal model was adapted for simulating the heating costs of the HVAC system in three scenarios. This simulation delivered the evaluation of the effectiveness of our system.

The findings of this study revealed that the current New Zealand BIM adoption was still early while the majority of existing BMSs here were not intelligent enough to maintain the energy efficiency. It was further verified that the solution is flexible and capable to be

applied on the New Zealand's situation in relation to educational facilities management. As a result, this study identified that BMS saved 1.52% heating costs in a New Zealand educational building whereas BIM-BMS integration attributed a further 0.68% (totally 2.20%).

To emphasize the uniqueness of this study, a New Zealand context was considered to conduct this study. Whereas, a comparison to the results from other researchers all over the world was made to remain the generalization. Considering a wide-ranging variety of projects in different countries, building types, building systems, evaluation method, our findings are limited within the features of the pilot case. Other aspects were recommended in the future study for generalizing, complementing, and optimizing the outcomes of this study.

Lists of Abbreviations

AEC - Architecture, Engineering, and Construction

AEM - Abnormal Event Management

AI - Artificial Intelligence

AIM - Asset Information Models

AMV - Actual Mean Vote

ANOVA - Analysis of Variance

APEC - Automated Procedures for Engineering Consultants

API - Application Programming Interface

AR - Augmented Reality

AUTEC - AUT Ethics Committee

BAS - Building Automation Systems

BDS - Building Description System

BIAIM - Building Integrated Agriculture Information Modelling

BIM - Building Information Modelling

BIM-IKBMS - Building Information Model Integrated Knowledge-Based Building Management System

BrIM - Bridge Information Modelling

CAD - Computer-Aided-Design

Cas - Customer Attributes

CBR - Case-Based Reasoning

CDE - Common Data Environment

CIM - City Information Modelling

CIs - Correlation Indices

COBie - Construction Operations Building information exchange

CPU - Central Processing Unit

DPs - Design Parameters

DSM - Design Structure Matrix

DSM - Dynamic Simulation Modelling

FaIM - Farm Information Modelling

FDI - Fault Detection and Isolation

FEA - Finite Element Analysis

FFSC - Fault-Finding Supervisory Control

FM - Facility Management

FMI - Functional Mock-Up Interfaces

FoIM - Forest Information Modelling

FRs - Function Requirements

f-BIM - Federal BIM

GIS - Geographic Information Systems

GUID - Globally Unique Identifier

h-BIM - Holistic BIM

IB - Intelligent Buildings

ICT - Information and Communication Technology

IDEF - Integrated Computer-Aided Manufacturing DEFinition for Function Modeling

IFC - Industry Foundation Classes

IKMN - International Knowledge Management Network

IoB - Internet of BIM

IoT - Internet of Things

IP - Intelligent Property

IPD - Integrated Project Delivery

IT - Information Technology

i-BIM - Integrated BIM

JSON - JavaScript Object Notation

KBS - Knowledge-Based System

KM - Knowledge management

KMS - Knowledge Management System

LAN - Local Area Networking

LCA - Lifecycle Assessment

LOD - Level of Development

MEP - Mechanical, Electrical and Plumbing

MR - Mixed Reality

MVD - Model View Definition

M2M - Machine-to-Machine

NASA - National Aeronautics and Space Administration

nD - Multi-Dimensional

n-BIM - Non-BIM

O&M - Operation and Maintenance

PIM - Project Information Modelling

PLC - Programmable Logic Controller

PMV - Predicted Mean Vote

PPD - Predicted Percentage Dissatisfied people

PPP - Product, Process, and People

PVs - Process Variables

RAD - Rapid Application Development

RBCs - Reconstruction-Based Contributions

RBR - Rule-Based Reasoning

ROI - Return on Investment

RTU - Remote Terminal Unit

SADT - Structured Analysis and Design Technique

SBSC - Simulation-Based Supervisory Control

SCADA - Supervisory Control and Data Acquisition

s-BIM - Standard BIM

WBS - Work-Breakdown Structure

WFB - Word-Frequency-Based

WTDA - Word-Frequency-Based Topological Data Analysis

UI - User Interface

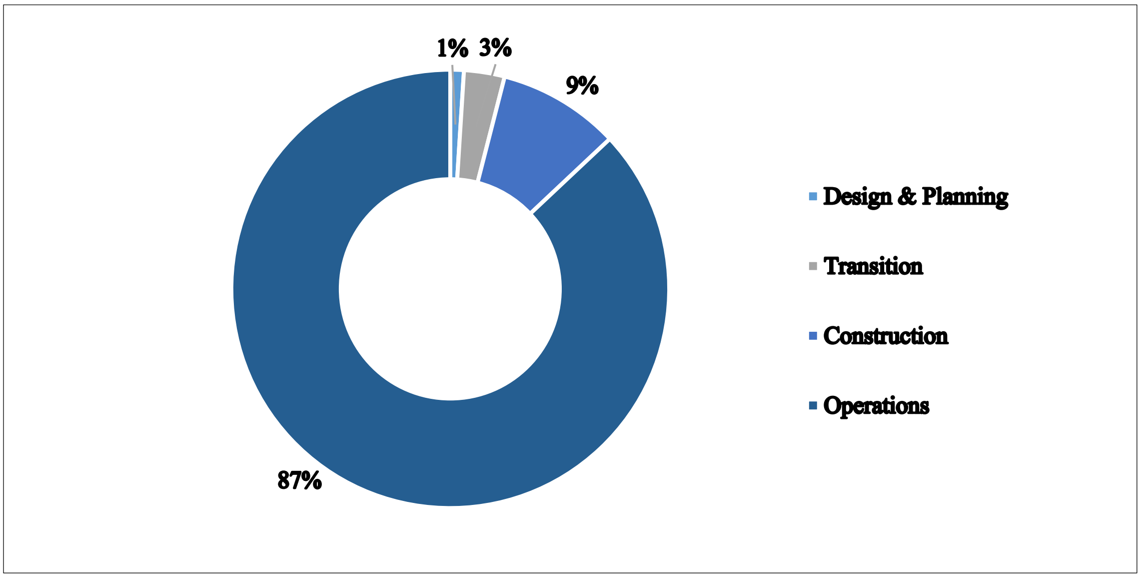
VR - Virtual Reality

WAN - Wide Area Network

Chapter 1 Introduction

1.1 Background

In recent years, the building sector and its people's activities in buildings account for nearly 60% of the world's electricity consumption and approximately 31% of the world's total final energy use (GEA, 2012). Surveys such as that conducted by Amitrano(Ed.) et al. (2014) have shown that by 2014, there were 41,154 ±1,286 non-residential buildings while around 1.5 million occupied dwellings in New Zealand. Besides, recent evidence suggests that the number of building consents issued is increasing rapidly (Statistics New Zealand, 2016). This number urges the efficient energy use in the building sector. From an economic perspective, the building costs in operation phase account 87% of total costs in the whole building lifecycle (See in Figure 1). Among these costs, energy consumption accounts for a significant proportion and higher than in any other building lifecycle (Clarke, 2008; G. Li, Kou, & Wang, 2019; M. Lu & Lai, 2019; C. Zhang, Nizam, & Tian, 2018). Hence, facilitating sustainable performance in the building Operation & Maintenance (O&M) phase can play an essential role in addressing the challenges above.



Source: BCPP (2016).

Figure 1 Proportional Split of Building Lifecycle Costs.

1.2 Research Problem

In the past, facility managers adopted the stand-alone control, which is complicated to manage all numbers of operational facilities in a building. For many years, the facility maintenance staff were busy with numberless recording, inspecting and maintaining works (Becerik-Gerber, Jazizadeh, Li, & Calis, 2012). Nowadays, the Building Management System (BMS) has been introduced to the Architecture, Engineering, and Construction (AEC) industry. The integrated system makes facilities management flexible (Foteinaki, Li, Heller, & Rode, 2018; Lizana, Friedrich, Renaldi, & Chacartegui, 2018; Niu, Tian, Lu, & Zhao, 2019). This fact has motivated the engagement of smart sensors, and optimization and control algorithms (Klein et al., 2012). Towards this end, there is a growing body of literature that recognizes the importance of adopting certain BMS throughout the O&M phase (Ippolito, Riva Sanseverino, & Zizzo, 2014). The BMS is defined as a computer-based building control system that controls and monitors the building facility systems (GhaffarianHoseini, Zhang, et al., 2017; Puķīte & Geipele, 2017). In this regard, trade-offs between building thermal comfort and building energy performance are made by using relevant BMS in the Operation and Maintenance (O&M) phase (Y. Chen, Liu, & Shi, 2018; Shaikh, Nor, Nallagownden, & Elamvazuthi, 2018).

However, the current information management in O&M still suffers from information peculiarity and fragmentation (Chuck Eastman, 2008; Pärn, Edwards, & Sing, 2017; Ricardo, Arto, Sergio, & Cecilia Gravina da, 2013). The massive amount of operational data in BMS still gives Facility Management (FM) staff a headache (Akhtar, Khan, Tarba, & Jayawickrama, 2018). This situation might be further exacerbated in buildings that are more complex, particularly in educational buildings (Saeed Reza Mohandesa, 2014).

1.3 Research Aim, Research Question, and Research Objectives

With the fast development of information technology, the current building facility O&M suffers from the increasing amount of operational and maintenance data. To address this issue, the primary research aim of this study is to investigate the effectiveness of BIM-BMS integration in managing existing educational building facilities in New Zealand. The research question of this study is "To what extent can BIM-BMS integration improve energy efficiency on managing existing educational facilities in New Zealand?"

Before conducting this study, the literature suggested integration of Building Information Modelling (BIM) and BMS. BIM is considered as the leading technology for use in the building sector (Ding, Zhou, & Akinci, 2014; Farr, Piroozfar, & Robinson, 2014). BIM is a process containing the generation and management of digital representations of physical and functional characteristics of building elements (National Institute of Building Sciences, 2007). It has a critical role in enhancing the effectiveness of project delivery, especially in facility management applications (Ding et al., 2014; Volk, Stengel, & Schultmann, 2014). BIM's introduction to the building sector is a contributing factor towards the improvement of productivity (Fountain & Langar, 2018; Herr & Fischer, 2019; Jang & Lee, 2018; J. Lee, Park, Choi, & Han, 2017). In addition, nD (multi-dimensional) facility information integration in the BIM database promotes its operative capacity (Farr et al., 2014). It has been suggested by researchers that relevant building energy consumptions can be reduced by effective building information management (Jiang, Chen, Hou, & Liu, 2018; Lawrence et al., 2012; Yoon et al., 2018).

During the O&M phase, object-oriented BIM models can be linked with BMS data (Farzaneh, Monfet, & Forgues, 2019; Matarneh, Danso-Amoako, Al-Bizri, Gaterell, & Matarneh, 2019; A. H. Oti, E. Kurul, F. Cheung, & J. H. M. Tah, 2016; Reginald, 2015). Hence, visual elements can be paired with physical elements. A connection between sensory nerve of the facility managers and the control panel of building facilities will be achieved once such system can be attached to Augmented Reality (AR) (Baek, Ha, & Kim, 2019), Virtual Reality (VR) (Shi, Du, Lavy, & Zhao, 2016), and Mixed Reality (MR) (Shi et al., 2016) wearable devices. Despite, both the hardware requirements and the operating costs should be reduced. Therefore, an integration of BIM and BMS is expected to improve the effectiveness of building O&M information management.

Table 1 Research Question, Research Aim and Research Objectives.

Research Aim
To investigate the effectiveness of BIM-BMS integration in managing existing educational building facilities in New Zealand.
Research Question
To what extent can BIM-BMS integration improve energy efficiency on managing existing educational facilities?
Research Objectives
(1) To define the New Zealand Specific BIM and its related terminologies. (2) To identify the current barriers towards a BIM-BMS integration for managing existing educational facilities in New Zealand. (3) To design a functional framework towards a BIM-BMS integration for managing existing educational facilities in New Zealand. (4) To develop a working prototype for managing existing educational facilities in New Zealand. (5) To evaluate the energy savings from a BIM-BMS integration on managing existing educational facilities in New Zealand.

However, BIM in New Zealand is still in its cradle (BIM Industry Training Group, 2016). A lack of empirical data for BIM use in FM exacerbates the resistance of adopting BIM-BMS integration. Towards this end, the primary objective of this study is to investigate the effectiveness of BIM-BMS integration in managing existing educational building facilities in New Zealand.

Prior to commencing this study, new definitions for BIM and its related terms should be made based on the New Zealand context. This is a pre-condition for applying BIM in New Zealand. There are already numbers of definitions for BIM and related terms available in the literature. However, none of them were established with consideration of the New Zealand context. This situation fails to acclimatize the BIM as well as the BIM-BMS adoption in New Zealand. Hence, this study is conducted upon a New Zealand based BIM and its related terminologies.

After that, the current barriers to adopting BIM-BMS integration in New Zealand are identified. The barriers to integrating BIM and BMS were already identified by the researchers from all over the world (A. H. Oti et al., 2016). However, these barriers might either too theoretical or not fit into the New Zealand AEC/FM industry. Removing these barriers are not expected to improve the effectiveness of building O&M information management in New Zealand. Hence, this study should find the potential barriers from the literature and then filtered with the New Zealand AEC/FM industry conditions.

Then, a functional framework is designed. There are already several software solutions covering one or more features of the BIM-BMS integration. However, they were developed for single-project-based, and with limited generation in New Zealand AEC/FM industry. On the other hand, with the fast development of Information Technology (IT), the individual parts inside a system keep on evolving. This reveals that some solutions might be effective at this time but will probably lose their effectiveness sometime later.

Both considered, a functional framework should be established considering both the generalization in New Zealand and the evolution of technology.

Next, a prototype is developed for testing the proposed framework. For a framework to succeed, a pilot test is required to be made for validating the effectiveness of using it. Prior to this, a prototype with software and hardware deployed is prepared. To maintain the generalization and adaptiveness of the proposed system, the proposed framework might be designed with much more functions from merely integrating BIM and BMS. However, these functions are not actually necessary for our primary aim. The prototype is developed based on the BIM-BMS integration related parts in the framework.

Lastly the prototype is be tested in a pilot case. This pilot test was conducted in a New Zealand existing educational building. The outcomes of the pilot testing are expected to validate the effectiveness of the proposed solution for the research problem.

This study intends to meet the research aim by providing a solution for the research problem. To achieve the research aim, five objectives were selected. The research aim and objectives can be found in Table 1.They follow the following sequence: first, it refines the basic terminologies for the research subject area in a specific context. After that, it identifies the barriers for solving the research problem in the specific context. Then, it provides a solution for removing these barriers. Next, it develops a prototype for the solution. Last, it evaluates the effectiveness of the prototype to validate the proposed solution.

1.4 Investigating questions

To achieve the objectives, 20 investigating questions were designed (See Table 2). A terminology base is obtained for this study. For reforming the terminology of BIM in a New Zealand context, the terms, such as BIM, BIM maturity, BIM dimensions, and so on, were defined. In addition, the global barriers paired with their potential solutions for practicing BIM in each maturity level is identified. Second, the global barriers and suggestions were filtered with a New Zealand context. For identifying the current barriers for the research problem, the current limitations of BIM, BMS, and BIM-BMS integration in New Zealand were surveyed. Third, a solution was designed under the specific suggestions towards removing these particular barriers. For designing a solution, a functional framework was modularized. The functions for each module and its sub-modules were defined. Following this, a prototype was prepared before the pilot testing carried on. For deploying both of the software and hardware for such prototype, the Supervisory Control and Data Acquisition (SCADA) levels, database types, and graphic libraries were determined. Finally, the pilot test was conducted. For validating the effectiveness of using BIM-BMS integration, the energy savings were measured. Wherein, the attributes from both BIM and BMS were clarified.

Table 2 Research Objectives with Investigating Questions.

Objectives	**Investigating Questions**
1. To define the New Zealand Specific BIM and its related terminologies.	Q1: How should BIM be defined in a New Zealand context? Q2: How can BIM maturity levels adapt to a New Zealand context? Q3: What are the barriers paired with the potential solutions for practicing BIM in each maturity level?
2. To identify the current barriers towards a BIM-BMS integration for managing existing educational facilities in New Zealand.	Q4: What is the relationship between BIM and BMS? Q5: What is the current BIM adoption in New Zealand? Q6: Is the BIM-BMS integration significant in supporting FM in New Zealand? Q7: What are the current limitations for BMS without BIM? Q8: Why are the current BIM-BMS integration cannot satisfy the expectations?
3. To design a functional framework towards a BIM-BMS integration for managing existing educational facilities in New Zealand.	Q9: What is the significance of adopting the proposed framework? Q10: How can the other functions be achieved in the future? Q11: What are the functions of the proposed framework?

	Q12: What functions should be adopted from the proposed framework towards promoting BIM-BMS integration at this stage?
4. To develop a working prototype for managing existing educational facilities in New Zealand.	Q13: Which level of SCADA should be adopted at this stage? Q14: What kind of database should be used at this stage? Q15: Which graphic library can be used at this stage? Q16: How can this solution generalized to non-expert industry end users.
5. To evaluate the energy savings from a BIM-BMS integration on managing existing educational facilities in New Zealand.	Q17: What is the tangible function of the proposed system that can direct to savings? And how much is it? Q18: What is the attribute from BMS? Q19: What is the attribute from features in the proposed system rather than BMS? Q20: How can the proposed solution generalized to the other existing buildings in New Zealand?

1.5 Research Methodology

The research focus and methodology have been gradually developed in keeping with the research questions. Given the nature of the research problem and the various data collection methods available, it is appropriate to employ a mixed methods approach.

Creswell and Clark (2007) suggested the mixed methods research is "a research design with philosophical assumptions as well as methods of inquiry", which "involves philosophical assumptions that guide the direction of the collection and analysis of data and the mixture of qualitative and quantitative approaches in many phases in the research process".

On the one hand, a qualitative approach is usually adopted in an exploratory study which makes observations to develop a theory (Reiter, 2017). Such study conducts inductive reasoning for contextualization. As a result, it usually delivers an understanding of the underlying reasons, opinions, and motivations (Mansourian, 2008).

For investigating the effectiveness of the proposed system, a qualitative approach is effective to provide an insight into the system design and development. However, such approach is deficient to measure how effective a system is in a reliable way (Creswell & Clark, 2007)

On the other hand, a quantitative approach is widely used in a confirmatory study which makes observations to test the theory. Such study carries on deductive reasoning by quantifying the problem using measurable data. Consequently, it generally formulates facts and uncovers patterns in research. With a prototype geared up in a pilot, a quantitative approach is capable of measuring its effectiveness in real-world operating. However, such approach is weak in transforming the context into the fruitful insights for theory exploring (Amaratunga, Newton, Baldry, & Sarshar, 2002).

All things considered, insufficient arguments will be provided by a single method for the research objectives and questions of this study. Therefore, the mixed methods approach was selected for this study for the reason that the research objectives and questions will benefit from a combination of both qualitative and quantitative approaches for the purposes of triangulation, complementarity, development, initiation, and expansion.

In addition, a comparison among different research approaches has been conducted by this resarch. Case study is an in-depth analysis of particular event or case over a long period of time. Researchers can observe but generally don't take part in the research study. However, there is no case study for BIM-BMS integration in NZ. This study has to develop the solution and apply on a pilot case. Thus, case study research approach is not suitable for this research.

Action research is a type of a research study that is initiated to solve an immediate problem. However, the solution of this research is not clear at the beginning. It requires a process of qualitative data collection and analysis for the specific suggestions. Hence, action research approach is not suitable for this research.

In an experiment, a researcher assigns a treatment and observes the response. However, this study needs a process of developing instrument which do not exist in NZ. Hence, a research approch which contains both development of instrument and test of instrument can be more suitable for this study.

There are four major types of mixed methods designs: triangulation design, embedded design, explanatory design, and exploratory design (Creswell & Clark, 2007). Simultaneously, two kinds of design modes exist: sequential and concurrent mixed methods research. Wherein, our research belongs to the sequential exploratory design. Greene, Caracelli, and Graham (1989) suggested that the results of the first method (qualitative) can help develop or inform the second method (quantitative) in an exploratory design (van Griensven, Moore, & Hall, 2014). The sequential exploratory design is useful when developing and testing a new instrument (Amaratunga et al., 2002; Creswell, 2003; Taguchi, 2018). The sequential model of the exploratory design has been illustrated in Figure 2.

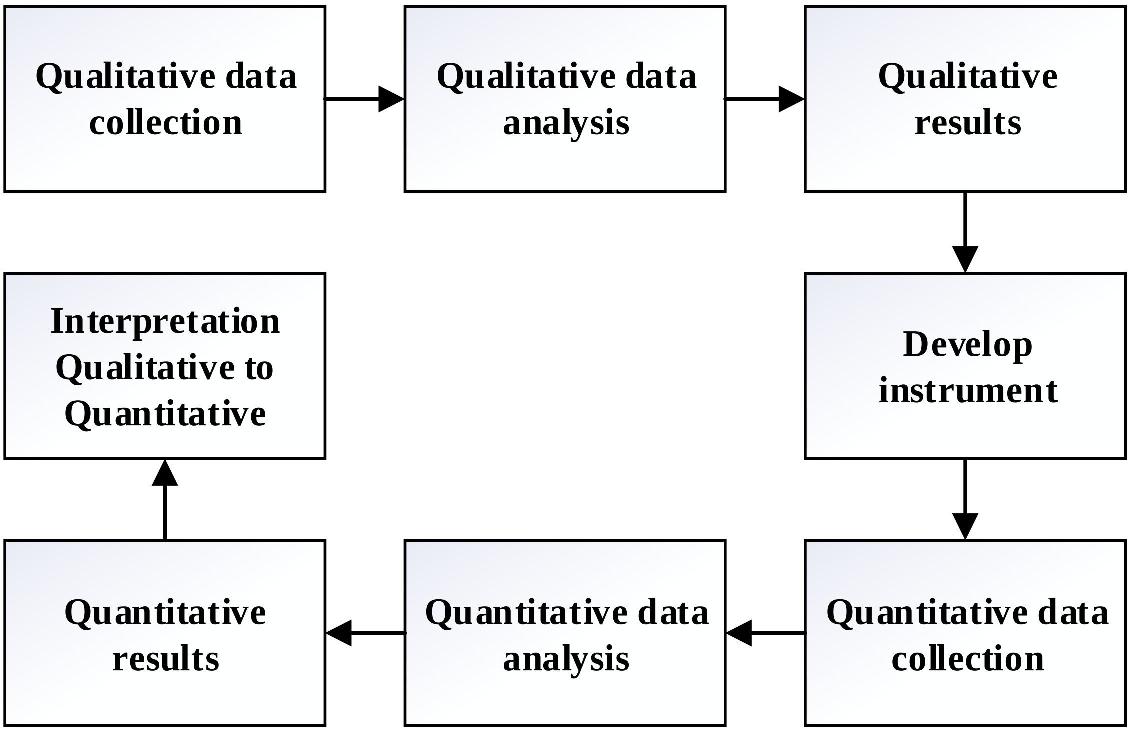


Figure 2 Exploratory Design: Sequential Model (Creswell & Clark, 2007).

Data for this study were collected using: a focus group interview and a pilot test. Prior to commencing the focus group, the investigating questions were designed based on the literature review. Then, qualitative data were collected in the roundtable and analyzed thematically. Since, the hypotheses for the quantitative phase were determined from those results. Based on the findings from the qualitative phase, a solution for solving the research problem was designed while a prototype with software and hardware deployed was prepared in a pilot case. After that, a pilot test was made to measure the effectiveness of our proposed solution. Wherein, numeral data such as the temperature, humidity, and air pressure were collected. In the quantitative analysis, the effectiveness of the BIM-BMS integration was quantified into the energy savings by using our prototype. Finally, the results of the quantitative phase were used to validate the findings in the qualitative phase.

1.6 Research Scope and Limitations

This study aimed to improve the effectiveness of building O&M information management in New Zealand only, but not concerned about any buildings in other countries. Wherein, only educational buildings were tested, but not selected the other types of buildings. Meanwhile, only the BIM-BMS integration solution was examined, but not considered other solutions which might also promote the sustainable building performance. Besides, this study used energy savings as the measurement indicator, but not adopted other indicators such as thermal comfort, and so on. In more details, this study is composed of five parts.

First of all, to reform the BIM and its related terminologies, it conducted a systematic literature review among publications from Elsevier, Springer, Taylor and Francis between 1995-2018. Such terminologies were established based on a global context. It might be generalized to a global context but only validated in the New Zealand context. The terminologies included BIM and its related terminologies only, but not covered other terms.

Then, it carried on a focus group interview recruiting New Zealand FM-related experts with more than 25 years of industry experience. This focus group interview identified the specific barriers of New Zealand BIM adoption, and current limitations for New Zealand FM using BIM, BMS, or BIM-BMS integration, but not concerned these conditions in other countries.

Next, this study designed a functional framework based on independent and information axioms for improving the effectiveness of building O&M information management in a theoretical perspective only, but not considered the current BIM and BMS adoption. Some of the functions were selected to address in this study; others were left for the future research due to the limited resource and utilities at the current maturity level in New Zealand.

Then, this study developed a prototype only for integrating BIM and BMS by adopting a SCADA system architecture, but not embedded in a Knowledge-Based System (KBS) which should be done in the next maturity level of New Zealand BIM. Such prototype was tested on a selected New Zealand educational building. Wherein, only HVAC system was tested, but not concerned other building systems though the prototype was eligible to run other systems.

Last, due to the time consumption, only winter case in Auckland was tested, but not concerned other seasons or other cities.

1.7 Thesis Outline

The structure of the thesis comprises 12 chapters as outlined below.

Chapter one provides an overview of the research beginning with the background to the study followed by the justification for conducting the current research. The next section presents the aims, objectives, investigating questions of the study followed by the research questions. The chapter further outlines the overview of the adopted research methodology for the study. The last section presents the scope and the limitations of the study and the outline structure of the thesis.

Chapter two delivers a general background of BIM fundamental conceptions, particularly definitions, dimensions, disciplines, stakeholders, lifecycle management, projects and maturity levels.

Chapter three delivers the global barriers coupled with suggestions of solving the research problem from the literature. It reviews building automation systems, building description systems and knowledge-based systems. This chapter also introduces the evolution of those technologies. Foremost, this chapter examines the New Zealand contexts for adopting those technologies.

Chapter four describes the theoretical and conceptual frameworks, coupled with the research methodology adopted for the conduct of this study. It begins with outlining the theory of the study and the development of the nD BIM-IKBMS conceptual framework. After that, an overview of the whole process is given, followed by a detailed description of each stage. Furthermore, the data collection and analysis process is described. This chapter also discusses the research design including philosophical assumptions and the rationale for the research approach used.

Chapter five presents the findings from documentation analysis. This chapter defines the BIM related terminologies in a New Zealand specific context. This chapter also outlines the maturity of BIM adoption in New Zealand.

Chapter six examines the results and analysis of the focus group interview. This chapter indicated New Zealand specific barriers coupled with specific suggestions. These barriers were expected to be removed by adopting the specific suggestions

Chapter seven designs the framework for the proposed solution and verifies its interoperability and flexibility. The proposed solution was designed and developed following the specific suggestions.

Chapter eight develops a working prototype representing the proposed solution. This chapter begins with developing a process model, and then provides a detailed description on each step wherein.

Chapter nine analyses the findings and results of the pilot testing. This chapter evaluates the effectiveness of adopting the proposed solution by demonstrating the energy savings that was obtained from adopting the proposed system.

Chapter ten discusses the research findings by collating the results from both qualitative and quantitative analysis. Essentially, this chapter responds to the presented research problem. Last, this chapter concludes after a wide discussion of the research findings.

Chapter eleven concludes the thesis by integrating the key research findings in relation to the research objectives. This chapter represents the research contributions to knowledge and practice, and provides a list of recommendations for the improvement of the productivity of New Zealand built environment. Besides, the research limitations were given. Finally, this chapter suggests opportunities for the future research arising from the current study.

Chapter 2 Research Background

2.1 Introduction

This research promotes the applications of BIM in the operation stage. The purpose of this chapter is to set a background of BIM in several aspects and identify the global barriers coupled with suggestions for the research problem from the literature. Towards obtaining an efficient solution, technologies suggested in global such as BAS, BDS, KBS, BPS, and FDI will be explored in their history and evolutions. Another critical aspect of this research was the subject-field evaluation methods. The potential measurements will be given in this section. After that, this study will explore the New Zealand context for doing this research. Such exploration will be of vital importance to determine the data collection methods. Finally, a discussion on the current BIM research in New Zealand reconfirm the significance of this study.

Numerous industry trends suggest a growing role for BIM as an evolution in the AEC industry (Luo & Gong; J. Wang et al., 2015). Extensive academic research has explored the BIM capacity in a single project categorized as four main topics:

(1) Multi-dimension conception.

An nD BIM model is maintained as a database for retrieving and sharing project information (J. Park & Cai, 2017; Y. Song, A. Hamilton, & Wang, 2007). BIM is richer in informatization and involves more dimensions than single 3D graphical entities in CAD. Particularly, the concept of ‘nD BIM’ comprehensively describes the complex hierarchies of building information (GhaffarianHoseini, Zhang, et al., 2017). In principle, such “nD BIM” model provides excellent opportunities for sensing, analysis, and communication of construction performance among project teams (K. K. Han & Golparvar-Fard, 2017).

(2) Multi-discipline federation.

A 3D design environment integrates a multi-discipline and object-based source of information in the AEC domain (Mejlænder-Larsen, 2017). A process of sequentially overlaying and comparing drawings for multi-systems is popularly used in the traditional MEP coordination, which is not time and money efficient (J. Wang, Wang, Shou, Chong, & Guo, 2016). 3D visual inspection detects the spatial and functional interferences in advance and eliminates the potential threat of 2D inconsistency (Weilun Lee1, 2015).

(3) Multi-stakeholder cooperation.

A single BIM software solution enables multi-discipline teams' collaboration. This software stores all project information securely in a standardized manner and serves as a data repository (Walasek & Barszcz, 2017). Most importantly, BIM enables all project participants to communicate with one another efficiently and avoids inefficient paper-based Requests for Information (F.H. Abanda, 2015; C.-Y. Lee, Chong, & Wang, 2016). Additionally, a distributed cloud-based BIM framework has been established towards an improved, more efficient means of collaboration among all the project stakeholders (Zahra Pezeshki & Ivari, 2016). Useful tools including ConjectPM, ThinkProject, Trimble Connect, and A360 allow users to keep documents up to date and all participants in the loop (Walasek & Barszcz, 2017). While Bentley Systems' Projectwise, Citrix Systems' GotoMeeting, Cisco Systems' WebEX, Smart Technologies' Smartboard, and Autodesk's Buzzsaw facilitate the Integrated Project Delivery (IPD) (Ma & Liu, 2014).

(4) Multi-lifecycle management.

A Common Data Environment (CDE) stores project documents including both graphical and non-graphical data for and from the whole project team. Such environment has been proved efficient in facilitating lifecycle collaboration and avoiding duplication and mistakes (F.H. Abanda, 2015). The built environment goes through several changes over its lifecycle, starting from the design phase through the construction phase and finally to the operation and maintenance (O & M) phase (M. Das, J. C. Cheng, & S. S. Kumar, 2015a). By adopting a CDE, the interoperability, the possibility for information to be transformed from one end user to the next throughout the lifecycle of a project, has been improved significantly (Zahra Pezeshki & Ivari, 2016). By adopting BIM, an accurate building model with precise geometry and corresponding non-graphical data can be established in a CDE throughout the building lifecycle (H.-T. Chen, Wu, & Hsieh, 2013). In the built environment sector, such models enable a harmonious information sharing of resources for a building entity to make up a reliable source for decision making throughout the whole lifecycle (C.-Y. Lee et al., 2016; S. Lee & Yu, 2017; Marchini & Patzlaff, 2016b).

However, little research has been conducted on the BIM uses in inter-project interoperability (Arayici, Fernando, Munoz, & Bassanino, 2018). Inter-project interoperability includes the knowledge interaction effect. Good examples for such effect are KBS for design optimization (Welle, Rogers, & Fischer, 2012), building maintenance (GhaffarianHoseini, Zhang, et al., 2017), and construction risk management (Zou, Kiviniemi, & Jones, 2017a).

Also the spatial interaction effects also challenge BIM interoperativity capacity, such as excavation (Qing, Heming, Yue, & Jing, 2013), wind flow (Quan et al., 2014), solar accessibility (SAKINÇ & SÖZEN, 2012), and provision of broadcast and other wireless services (Ofcom, 2009). In addition, social interaction cannot be emphasized more in the building operation stage, such as hazard evacuation (McCaughey, Mundir, Daly, Mahdi, & Patt, 2017) and urban planning (Frankhauser, Tannier, Vuidel, & Houot, 2018).

Last, economical interaction should also be taken into account for this aspect, such as cross-project budget planning and cost tracking (Caniëls & Bakens, 2012), energy management (Y. Han & Taylor, 2015), and environmental sustainability (Säynäjoki, Heinonen, & Junnila, 2014); and industry inference effect (Mersal, 2017) etc.

2.2 BIM Definitions

In the field of AEC/FM, various definitions of BIM are found. In short, they are ill-defined concepts that are often used interchangeably. Regardless, BIM was popularly defined as either a digital representation or a process for specific AEC/FM uses. However, BIM was defined differently in different time and maturity levels:

(1) The definitions before 2005.

According to Migilinskas, D. (Migilinskas, Popov, Juocevicius, & Ustinovichius, 2013), an earlier BIM was building's graphical 3D model enriched by additional intelligence (information associated with graphics). In 1975, C. Eastman and et al. first coined the concepts of Building Description System (BDS) in a research report (Charles Eastman et al., 1974) and identified the general purpose of BDS in 1976 (C. Eastman, 1976). In 1995, C. Eastman and S. Anastassios defined a building model as

> "A building model is a representation of the building overall its life stages that is adequate for most (if not all) uses. This includes feasibility studies, all aspects of design and construction, and later, operation and facility management."
>
> C. M. Eastman and Siabiris (1995)

At this stage, a Generic Building Model was introduced as a kernel backend repository capable of being extended with any architectural or building design applications. Three main types of information were mentioned in such a model: building constructed form, bounded space, and activities. In the same year, S. Ford and et al. established a multi-dimension object model and emphasized data, process, and activities (S. Ford et al., 1995). Hence, we found that a multiple-dimension conventionalization was made at this stage while building design works were the main focus. In addition, building lifecycle engagement has been indicated as a future study.

(2) The definitions between 2005-2009.

More specifically, BIM began to be defined as a digital tool. Associated General Contractors Guide defined BIM as “a data-rich, object-oriented, intelligent and parametric digital representation of the facility from which views and data appropriate to various users’ needs can be extracted and analyzed to generate information, which can be used to make decisions and improve the process of delivering the facility” (Associated General Contractors of America, 2007). Whereas the National Institute of Building Sciences buildingSMART alliance (2007) defined BIM as “a digital representation of the physical and functional characteristics of a facility” in NBIMS v1. While NBS (2016) defined the output of BIM as “the digital description of every aspect of the built asset”. McFarlane (2008) indicated that “BIM takes a multi-dimensional approach, allowing the building team to see how the pieces of their project fit together in real time”. Similarly, Gunderson (2012) defined BIM as an object-based and data-rich parametric digital representation of a project. Isikdag, Underwood, and Aouad (2008) examined the common and definitive characteristics of BIM by analyzing the definitions in this time range, and two main definitive characteristics of BIMs were identified - interoperability, and data sharing and exchange. With these characters, this digital tool was expected to coordinate a multi-discipline design process with multi-stakeholders. This can be achieved by enabling the integration and reuse of building information and domain knowledge (Ghang Lee, Rafael Sacks, & Eastman, 2006). In this stage, Building Lifecycle Management (BLM) was mentioned again, but only a few practical pieces of evidence were found.

(3) The definitions between 2010-2014.

During this stage, BIM was promoted with its interoperability and as a digital tool/process/model/database/etc (Teicholz, Sacks, & Liston, 2011). More evidence in practice was found supporting a BIM-facilitated multi-discipline/multi-stakeholder collaboration (I.A. Ocheoha & Moselhi, 2013). However, the main focus was to promote BIM in the multi-stakeholder and multi-lifecycle federation. Meanwhile, many researchers globally provided an updated definition of BIM: Czmoch and Pękala (2014) noted that buildingSMART remained a digital representation ontology for BIM but updated the BIM definition with a whole lifecycle perspective in 2011. In contrast, Migilinskas et al. (2013) indicated that "BIM technology takes new meanings, highlighting the generic concepts of this universal determination for product deliverables build on usage of building intellectual 3D virtual model associated with this processes like project inception, design, evaluation, construction, operation and demolition". British Standard Institution (2013) defined BIM in PAS 1192-2:2013 as "the process of design, construction and use of the building or facility infrastructure using information about virtual objects".

(4) The definitions between 2015-2018.

This research didn't find any updated version of BIM definition during 2015-2018. Defining BIM was not a focus in the latest years anymore. Instead, massive topological terms from BIM were identified. These included Bridge Information Modelling (BrIM) (Arayici et al., 2018; Gupta, Cemesova, Hopfe, Rezgui, & Sweet, 2014). Forest Information Modelling (FoIM) (Tianyang, Qiaohong, Jing, & Wenjie, 2010). Farm Information Modelling (FaIM) (Kruize, 2015), and Building Integrated Agriculture Information Modelling (BIAIM) (Khan, Aziz, & Ahmed, 2018). Meanwhile, City Information Modelling (CIM) (Deng, Cheng, & Anumba, 2016), and Project Information Modelling (PIM) (Bradley, Li, Lark, & Dunn, 2016) were emphasized more frequently.

2.3 BIM Dimensions

According to S. W. A. Lee, A.J. Marshall-Ponting, G. Aouad, R. Cooper, I. Koh, C. Fu, M. Betts, M. Kagioglou, M. Fischer (2003), "'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" was first coined by the University of Salford (S. W. A. Lee, A.J. Marshall-Ponting, G. Aouad, R. Cooper, I. Koh, C. Fu, M. Betts, M. Kagioglou, M. Fischer, 2003; S. W. A. Lee, G. Aouad, R. Cooper, J. Tah, 2005) to complement the 3D modelling of buildings with time, cost, sustainability, accessibility and maintenance. An "nD model" is an extension of the BIM models by integrating all the design information for a building facility throughout all lifecycle phases (S. W. A. Lee, A.J. Marshall-Ponting, G. Aouad, R. Cooper, I. Koh, C. Fu, M. Betts, M. Kagioglou, M. Fischer, 2003; S. W. A. Lee, G. Aouad, R. Cooper, J. Tah, 2005).

Among these definitions, the term "3D BIM" can be translated to either building entities or spatial information: it commonly refers to x, y, and z. Upon 3D BIM, 4D BIM adds an extra dimension of time-related information. Paired with the scheduling, 5D BIM extracts accurate cost information, including predicted and actual costs.

There is wide consensus in 3-5D BIM explanations. However, disputes exist in the literature for BIM dimensions beyond. As one of the most popular used definitions, 6D is more commonly defined as sustainability while 7D refers to FM (Arunkumar, Suveetha, & Ramesh, 2018; Chegu Badrinath, Chang, & Hsieh, 2016; Czmoch & Pękala, 2014; M. Das, J. C. P. Cheng, & S. S. Kumar, 2015b; GhaffarianHoseini, Zhang, et al., 2017; Gourlis & Kovacic, 2017; Kacprzyk & Kępa, 2014; T. W. Kang & Choi, 2017; Redmond, Hore, Alshawi, & West, 2012).

According to Masood, Kharal, and Nasir (2014), both 6D and 7D BIM are used in the management of completed facility: 6D relates to sustainable development including energy consumption. 7D includes renovation and modernization planning, procedures and user manuals, inspection, and safety procedures (for example fire procedures).

However, numbers of publications gave a more general definition: they nominated 6D BIM as facility management (Badi & Diamantidou, 2017; Bryde, Broquetas, & Volm, 2013; Cha & Lee, 2014; Fadeyi; Joannides, Olbina, & Issa, 2012; Marchini & Patzlaff, 2016a; Masood et al., 2014; Nicał & Wodyński, 2016; Pärn et al., 2017).

According to Nicał and Wodyński (2016), 6D BIM is more properly linked with the post-construction phase. In this phase, BIM facilitates FM practices, which overlaps with the life-cycle performance of the building, including "sustainability".

Similarly, NBS defined 6D BIM dimensions as Project Lifecycle Information. Refer to McPartland (2017), 6D BIM is also known as "*i-BIM*", which involves the inclusion of information to support facility O & M to drive better business outcomes. Migilinskas et al. (2013) indicated that 6D BIM is PLM analogue for the construction industry.

Other definitions such as construction records (e.g., quality information, health and safety information, and contract information) (Wu & Hsieh, 2012), Work-Breakdown Structure (WBS) (J. Park & Cai, 2017), and safety information (Z. Du & Liu, 2010) are either defined narrowly or conflicted with other existing dimensions. For example, WBS is a part of scheduling works in a building construction project. Moreover, the occurrence of disputes can be minimized by giving a more general but accurate definition.

Upon the most general definition, "Project Lifecycle Information", from NBS, we refine the 6D BIM more accurately as "Post-Construction Lifecycle Information". This information covers not only traditional 6D and 7D information such as sustainability and

FM but also includes other information such as accessibility, evacuation (Rueppel & Stuebbe, 2008), etc.

2.4 BIM Disciplines

Various studies have demonstrated that BIM is efficient in facilitating multi-discipline federation (Doan et al., 2017; J. Du, Zou, Shi, & Zhao, 2018; F.H. Abanda, 2015; GhaffarianHoseini, Zhang, et al., 2017; Mejlænder-Larsen, 2016; Merschbrock & Munkvold, 2015; Ning, Kan, Zhifeng, Weihua, & Geert, 2018; Walasek & Barszcz, 2017; J. Wang et al., 2016; Weilun Lee1, 2015).

OCCS Development Committee Secretariat (2012a) defined disciplines as "the practice areas and specialties of the actors (participants) that carry out the processes and procedures that occur during the life cycle of a construction entity".

Different theories exist in the literature regarding discipline classification. According to S. Ford, Aouad, G., Kirkham, J., Brandon, P., Brown, F., Child, T., Cooper, G., Oxman, R., Young, B. (1995), there are three main types of disciplines: design, procurement, and management of construction. Similarly, Cha and Lee (2015) suggested those three types: management, engineering, and field execution. Baldwin, Shen, Poon, Austin, and Wong (2008) classified the design disciplines of architectural design, civil engineering design, structural engineering design, mechanical engineering design, and electrical engineering design.

However, academic discipline is defined as a branch of knowledge. Froese (2010) classified the academic discipline in AEC/FM as architectural, structural and building services. Such discipline specializes a branch of knowledge, which covers its design, procurement, and management of construction. Together these results provide valuable insights into discipline classification.

In this study, results in BIM articles suggest adopting a classification of architectural, structural, and building services rather than make this too complicated in a world context. First, architectural discipline defines the space and appearance of various architectural elements (Hu, Zhang, & Deng, 2008), such as walls, ceilings, doors and windows, stairs, roofs (C. M. Eastman & Siabiris, 1995). Available tools for architectural design include Revit from Autodesk, ArchiCAD from Graphisoft, Bentley Architecture and Digital Project from Gehry Technologies (Jeong, Eastman, Sacks, & Kaner, 2009). BIM techniques facilitate architectural process with 3D parametric design (C. M. Eastman & Siabiris, 1995; Succar, 2009b), energy analysis (S. Ford, Aouad, G., Kirkham, J., Brandon, P., Brown, F., Child, T., Cooper, G., Oxman, R., Young, B., 1995; Schlueter & Thesseling, 2009).

Next, structural discipline analyses the mechanical behavior of structures and structural components. Three types of information are involved in a structural BIM: structural elements, resistance models, and loading conditions (Hu et al., 2008). The structural elements included precast concrete, steel and cast-inplace reinforced concrete members (Jeong et al., 2009). Available tools include Bentley Structure, Revit Structure, Tekla Structures, Digital Project (CATIA-based), StructureWorks (Solidworks-based), etc. (Ghang Lee et al., 2006). A lack of 3D structural geometry transformation for structural analysis, especially Finite Element Analysis (FEA), is the main drawback of traditional structural design process without BIM (Shin, Lee, Oh, & Chen, 2011).

Finally, building services provide assemblies of a set of facility components. Building service elements cover Mechanical, Electrical and Plumbing (MEP) systems (Nepal, Staub-French, Pottinger, & Webster, 2012). Available tools include Revit MEP, MagiCAD, etc. (Allotta et al., 2017). A 3D visualized design is conducted on a BIM platform to facilitate the design of building service systems (J. Zhang, Long, Lv, & Xiang, 2016). According to Aram, Eastman, and Sacks (2013), some available BIM coordination software solution provide features to carry on the clash detection among interacting systems. Such features will reduce capital costs after construction commissioning (Love, Matthews, Simpson, Hill, & Olatunji, 2014). Those interacting elements will be located, commented and tracked until resolved.

Above all, a federal BIM refers to a BIM model with a multi-discipline federation (Solihin, Eastman, Lee, & Yang, 2017). With a federal BIM, the inter-discipline interaction can also be detected with structural elements (Jeong et al., 2009). Hence, the multi-discipline federal BIM can largely reduce construction time and costs, reduce errors, enhance fabricator productivity and improve building performance (Jeong et al., 2009).

2.5 BIM Stakeholders

More recent attention has focused on the provision of BIM on multi-stakeholder cooperation (Tao, Chunhui, Jinhui, & Cai, 2018; Tolmer, Castaing, Diab, & Morand, 2017). From a stakeholder perspective, BIM facilitates the collaboration among owners, designers, contractors, and management teams (Nam Buiab, 2016).

In Uniclass (RIBA Enterprises Limited, 2018), the stakeholders are classified as: PM_20_10 Organization roles; PM_20_20 Asset management and delivery roles; PM_20_30 Statutory roles; PM_20_40 Team lead roles; PM_20_50 Design roles; PM_20_70 Surveyor and planner roles; PM_20_80 Environmental and geological roles. In the OmniClass (OCCS Development Committee Secretariat, 2012b), the stakeholders are detailed as Entrepreneurial Roles: Owner, Partner; Management Roles: Strategic Management Roles, Operational Management Roles; Development Roles: Design Roles, Planning Roles, Surveyor, Contract Administrator, Observational Roles; Execution Roles: Procurement Roles, Construction Roles; Utilization Roles: Facility Use Roles, Facility Service Roles; Support Roles: Administrative Service Roles, Professional Service Roles; Group Roles: Teams, Boards, Committees, Business Organizations, Non-profit Organizations.

To compare the difference between those standards and our results, we found that few stakeholders are more suitable for a BIM content: occupancy, ownership, management, development, and execution.

Firstly, BIM has been demonstrated efficiently to deliver benefits for BIM entrepreneurial roles by representing the project needs: to maintain occupant comfort (Azhar, Carlton, Olsen, & Ahmad, 2011; Marzouk & Abdelaty, 2014a, 2014b; Zhao, Lam, Ydstie, & Karaguzel, 2015), to facilitate energy conservation (C. M. Eastman & Siabiris, 1995; Schlueter & Thesseling, 2009), and to reduce the maintenance costs (Fox & Hietanen, 2007; Succar, 2009b). A significant and growing body of literature has investigated the occupancy schedule (K. Kim & Yu, 2016; Welle, Haymaker, & Rogers, 2011) and highlighted the engagement of occupants/owners in BIM use (Zahra Pezeshki & Ivari, 2016; Yi, Braham, Tilley, & Srinivasan, 2017; Zhao et al., 2015). Building performance regarding to occupancy usually delivers direct or indirect benefits to the enterprise. Interestingly, this correlation is related to the features of comfort, energy conservation, and maintenance cost-efficiency. However, differences exist between ownership and occupancy. From an owner perspective, they actively preserve the above features to increase the value of the real estates. On the other hand, the occupants will be massively influenced by the building performance. Although there are still few enterprises which will not be impacted by the building performance, such cases are not within the scope of this study.

Secondly, BIM is proposed among multiple disciplines for development and execution roles which are both in charge of the delivery of a building project. In traditional projects, gaps exist between development and execution processes (Scottish Energy Centre (HEI) & The Morrison Partnership Ltd (SME), 2012): sustainable material selection (Hu et al., 2008; Isikdag et al., 2008; Jeong et al., 2009; Succar, 2009b), consideration of fabrication and installation (S. Ford, Aouad, G., Kirkham, J., Brandon, P., Brown, F., Child, T., Cooper, G., Oxman, R., Young, B., 1995; Ghang Lee et al., 2006; Jeong et al., 2009; Melzner, Zhang, Teizer, & Bargstädt, 2013), consideration of BMS deployment (Dong, O'Neill, & Li, 2014; Love et al., 2014; Marzouk & Abdelaty, 2014b; Riaz, Arslan, Kiani, & Azhar, 2014), etc. On the other hand, in IPD mode, which is promoted by BIM technologies (Cha & Lee, 2014; Farr et al., 2014), development and execution teams always work together with common profits (Succar, 2009b). Within a CDE, development and execution teams collaborate efficiently and avoid duplication and mistakes at an early stage (Abanda, Vidalakis, Oti, & Tah, 2015). According to Hiyama, Kato, Kubota, and Zhang (2014), front loading can maximize the efficiencies of the whole building lifecycle. However, at this stage, the public sector is not ready to throw BIM onto the level of IPD (Porwal & Hewage, 2013; Succar, 2009b). Refer to Smith (2014), IPD requires more widespread implementing and understanding. Hence, it was convinced that IPD, might not be realistically adopted shortly in most of the projects (Miettinen & Paavola, 2014).

Thirdly, BIM is capable of supporting the facility manager for information sharing, communication media, process management, exploration space, privacy and flexible system configuration (Singh, Gu, & Wang, 2011). Initially, through a 3D-based energy monitoring system, facility managers can intuitively confirm building energy consumption for each room. With this information, they can make a decision regarding the operation of building facilities (W.-L. Lee, Tsai, Yang, Juang, & Su, 2016). Meanwhile, an operation staff, who is unfamiliar with the complicated facility operation, can instinctively browse through the models (W.-L. Lee et al., 2016). Additionally, the facility manager can be alerted when a building component is due for an inspection

(Costin & Teizer, 2015), or informed a week before the expiration dates (W.-L. Lee et al., 2016). Hence, with the help of BIM, the management teams can directly access the needed information and efficiently arrange the maintenance tasks (Q. Lu, Chen, Lee, & Zhao, 2018).

Fourthly, BIM largely improves the efficiency of the development teams. Either instrument sketching or computer-aided drafting is intrinsically prone to human error; resulting in significant errors and change, which will apply to the works after design (C.M. Eastman, 2008). BIM is capable of cooperating design teams in all disciplines (Jeong et al., 2009), which has been emphasized in the previous section. With a multi-discipline federal BIM model, the designers can take advantage of 3D visual inspection for specific areas and find out the problem area in advance (W. Lee et al., 2015). Consequently, this avoids the blind spots in conventional 2D methods.

Above all, BIM has a potential life-cycle use at each stage of a project (Grilo & Jardim-Goncalves, 2010). It can be used in a range of ways. Owners can utlise it to understand project needs which will postpone the benefits to the occupants; by the development team to plan, design and survey the project.The execution team can use it to procure, manage, and conduct the project construction; and by the management team to operate and maintain the building. However, multi-stakeholder cooperation found in this study only refers to the cooperation within one single building lifecycle. “Multi-stakeholder” was defined by this study as the engagement of either one or few types of project roles in a specific project lifecycle. The results find that, currently, BIM is most commonly adopted in multi-stakeholder cooperation during the construction stage (Alwan, Jones, & Holgate, 2017; Melzner et al., 2013). Stakeholders from ownership/occupancy, development, execution, and management are all possible to be involved in this stage. However, in the design phase, some of nowadays’ projects might not engage the execution team to participate, which would maximize the inconsistency between design outputs and construction needs. Therefore, a fully developed BIM multi-stakeholder cooperation is expected to efficiently collaborate with all the stakeholders necessary in one specific project lifecycle phase.

2.6 BIM and Lifecycle Management

Some studies have begun to examine BIM lifecycle integration (Baldwin et al., 2008; Cerovsek, 2011; Dong et al., 2014; Ghang Lee et al., 2006; Gupta et al., 2014; Hu et al., 2008; Isikdag et al., 2008; Isikdag, Underwood, Aouad, & Trodd, 2007; Jiao et al., 2013; Leite, Akcamete, Akinci, Atasoy, & Kiziltas, 2011; S. Li, Isele, & Bretthauer, 2008; Love et al., 2014; Shin et al., 2011; Succar, 2009b; Succar, Sher, & Williams, 2013). Despite this, disputes exist in dividing the project lifecycle into separate phases.

Several organizations have accomplished their divisions. Some of them divided activities while others used phases. Refer to MasterFormat (The Construction Specifications Institute and Construction Specifications Canada, 2016), lifecycle activities are described as: 01 91 00 Commissioning; 01 92 00 Facility Operation; 01 93 00 Facility Maintenance; 01 94 00 Facility Decommissioning; while in Uniclass (RIBA Enterprises Limited, 2018) it is divided as Ac_05_00 Strategy stage activities; Ac_05_10 Brief stage activities; Ac_05_20 Concept stage activities; Ac_05_30 Definition stage activities; Ac_05_40 Design stage activities; Ac_05_50 Build and commission stage activities; Ac_05_60 Handover and close-out stage activities; Ac_05_70 Operation and end of life stage activities.

On the other hand, phases have been defined in UNIFORMAT II (Charette & Marshall, 1999). They are planning, programming, design, construction, and operations. In comparison, phases in OmniClass (OCCS Development Committee Secretariat, 2012c) are : 31-10 00 00 Inception Phase; 31-20 00 00 Conceptualization Phase; 31-30 00 00

Criteria Definition Phase; 31-40 00 00 Design Phase; 31-50 00 00 Coordination Phase; 31-60 00 00 Implementation Phase; 31-70 00 00 Handover Phase; 31-80 00 00 Operations Phase; 31-90 00 00 Closure Phase.

Together these results provide important insights into intersections in the project lifecycle activities. Some of these activities might go through one or more phases. This can be seen when a few projects conduct design, surveying, and construction at the same time.

On the other hand, academic classifications are more general. Most commonly, building lifecycle is divided into design, construction, and O&M stages. According to Succar (2009a), construction projects have three major lifecycle phases detailed with their sub-phases: Design phase: D1 Conceptualisation, programming and cost planning, D2 Architectural, structural and systems, D3 Analysis, detailing, coordination and specification design; Construction phase: C1 Construction planning and construction detailing, C2 Construction, manufacturing and procurement, C3 Commissioning, as-built and handover; and Operations phase: O1 Occupancy and operations, O2 Asset management and facility, O3 Decommissioning and major re-programming.

Previous research findings into the post-construction BIM uses have been inconsistent and contradictory. Building operation (Chong, Lee, & Wang, 2017; El-Diraby, Krijnen, & Papagelis, 2017; F.H. Abanda, 2015; Fox & Hietanen, 2007; J. I. Kim, Kim, Fischer, & Orr, 2015; Marzouk, Abdelkader, & Al-Gahtani, 2017; Motawa & Carter, 2013; Oti & Tizani, 2015; Santos, Costa, & Grilo, 2017; S.-H. Wang, Wang, Wang, & Shih, 2015; Yenumula, Kolmer, Pan, & Su, 2015; Zhao et al., 2015), building maintenance (Ghaffarianhoseini, Tookey, et al., 2017; Jung & Joo, 2011; Martínez-Aires, López-Alonso, & Martínez-Rojas, 2018; Marzouk et al., 2017; X. Wang, Truijens, Hou, Wang, & Zhou, 2014; S. Zhang et al., 2015), building O&M (Costin & Teizer, 2015; Das et al., 2015a; Davies & Harty, 2013; GhaffarianHoseini, Zhang, et al., 2017; Grilo & Jardim-

Goncalves, 2010; C.-Y. Lee et al., 2016; W.-L. Lee et al., 2016; Ning et al., 2018; Zheng, Lu, Chen, Chau, & Niu, 2017), building facility management (Dong et al., 2014; C. M. Eastman & Siabiris, 1995; T. W. Kang & Hong, 2015; Liao & Teo, 2017, 2018; Smith, 2016) are all used to describe the phase after construction handover, however, conflicts exist when adopting either one phase. Thus, in the New Zealand context, the divisions should avoid conflicts and be more reasonable.

Collectively, these studies outline a critical role for BIM in lifecycle uses. Before a design is commissioned, BIM tools are not widely used. In the design phase, BIM is a tool that coordinate multi-discipline design and is expected to output multi-discipline federated BIM models. When it comes to the construction phase, BIM is used to coordinate all the stakeholders. After the construction handover, BIM performs as an integrated repository for lifecycle information integrated, especially post-construction lifecycle information. Finally, BIM acts as a quantity tool for both demolition and recycling in the deconstruction phase.

2.7 BIM Interoperativity

It has been found that BIM is always used to support single project BIM practices. Nonetheless, the inter-project interoperability has become a central issue for the future BIM uses. Once a building is decided to be built, the influence on surroundings will start to be made. Those influences include knowledge, spatial, economic, society, and industry, etc. Successful interaction management on all aspects above is expected to deliver extra sustainability. To begin with, a KBS is demonstrated efficient to remain a specific domain of knowledge while keeping it up-to-date. When an issue occurs, Case-Based Reasoning (CBR) will be made to retrieve the solutions from past. Once the issue is resolved, the KBS will be updated. Recent evidence suggests that BIM-based KBSs have been used throughout the project lifecycle: design (Welle et al., 2012), construction (GhaffarianHoseini, Zhang, et al., 2017), and post-construction phases (Zou et al., 2017a).

Then, recent developments in civilization have heightened the need for spatial interaction management. One building might impact the other spatially in excavation (Qing et al., 2013), wind flow (Quan et al., 2014), solar accessibility (SAKINÇ & SÖZEN, 2012) and provision of broadcast and other wireless services (Ofcom, 2009), etc. Coupled with the BIM 3D visualization, the results are expected to be obtained more reasonably and efficiently.

Next, investigators have examined the interactive impacts of multiple projects from one single enterprise. Typically within a company, cross-project budget planning and cost tracking were carried on to assist the decision-making process (Caniëls & Bakens, 2012). When it comes to multi-building operation, energy management can facilitate the energy conservation (Y. Han & Taylor, 2015) while remaining environmental sustainability (Säynäjoki et al., 2014). Once BIM adopted, numbers of simulation on cost tracking and energy & environmental management will be made to deliver more sustainable results.

After that, the results of this research also suggest that society is also impacted when adding a new building to a specific site. Existing BIM models are potential to be used to promote urban planning (Frankhauser et al., 2018) as well as community-scale or city-scale hazard evacuation (McCaughey et al., 2017).

Last, recent trends in BIM have led to a proliferation of studies on developing topological term. Researchers all over the world start to develop information modeling/models in a specific sector rather than buildings, such as bridge (Arayici et al., 2018; Gupta et al., 2014), forest (Tianyang et al., 2010), farm (Kruize, 2015), agriculture (Khan et al., 2018), etc.

2.8 BIM Maturity Levels

The most popular used BIM maturity concept was developed by BIM Task Group (2011) in the UK. It defined four maturity levels:

(1) BIM Level 0: conventional Computer-Aided-Design (CAD) workflow;

(2) BIM Level 1: a clear role paired with its responsibilities, well naming conventions, code and spatial coordination arrangement, a CDE, and a well-defined document repository should be in place;

(3) BIM Level 2: built upon BIM Level 1, nD BIM is proposed in multi-discipline coordination, especially used in 4D (Scheduling) and 5D (Estimation);

(4) BIM Level 3: upon BIM Level 2, projects at this level are fully collaborative.

2.9 Summary

This chapter provided the research background of BIM subject. It reviewed the existing definitions, dimensions, disciplines, stakeholders, lifecycle views, project views, and maturity levels.

To begin with this chapter, the definitions were grouped based on the time. Whereby, it represented the development of such subject.

Then, the dimensions were examined. After a comparison among those disputes, it mainly identified the most suitable dimension division that BIM integrates multi-dimensional information including 3D entity, 4D time, 5D cost, and 6D Post-Construction Lifecycle Information; as for the disciplines, BIM covers architectural, structural, and building services. Likewise, the stakeholders were indicated as ownership/occupancy, development, execution, and management.

Next, the lifecycle was classified into planning, design, construction, post-construction, and deconstruction.

After that, the diversity of project type was highlighted. Provided that, BIM uses vary from one project type to another.

Last, the most popular used BIM maturity was given. Such maturity will be further refined to meet the requirements of New Zealand generalization. After getting the background, the next phase of this study was to review the existing research on the related technologies, which is provided in the next chapter.

Chapter 3 Literature Review

3.1 Introduction

The purpose of this chapter is to identify the global barriers coupled with suggestions for the research problem from the literature. Towards obtaining an efficient solution, technologies suggested in global such as BAS, BDS, KBS, BPS, and FDI will be explored in their history and evolutions. Another critical aspect of this research was the subject-field evaluation methods. The potential measurements will be given in this section. After that, this study will explore the New Zealand context for doing this research. Such exploration will be of vital importance to determinate the data collection methods. Finally, a discussion on the current BIM research in New Zealand reconfirm the significance of this study.

3.2 Global Barriers

3.2.1 BMS without BIM

Recently, sustainability has been emphasized during the whole building lifecycle (Oviir, 2016). Throughout the building lifecycle, O&M phase takes the longest duration as well as the most management and maintenance costs (BCPP, 2016). Thus, improving the post-construction sustainable performance plays a more important role than the other lifecycle. Towards this end, numbers of projects have involved a BMS in their facility management and maintenance activities throughout the O&M phase (Ippolito et al., 2014). As an energy-efficient solution, BMS (without BIM) enables both smart monitoring and automatic control for building operational facilities (Kučera, Glos, & Pitner, 2013). This benefits the operational and maintenance staff by providing a meaningful visualization for energy consumption profiles (A. Oti, E. Kurul, F. Cheung, & J. Tah, 2016). The historical energy performance represents a more comprehensive understanding of energy use for non-expert staff. However, the main weakness of BMS is the failure to address data analysis and structuring (A. Oti et al., 2016). Without data analysis, raw data will be fragmented. The capacity for capturing and reporting fragmented data cannot make contributions to a more sustainable post-construction performance (Molina-Solana, Ros, Ruiz, Gómez-Romero, & Martin-Bautista, 2017). Besides, unstructured data streams challenge the BMS users by its overwhelming amount (Fan, Xiao, Madsen, & Wang, 2015). Thus, BMS has exceedingly limited practicality in promoting post-construction sustainability without BIM.

3.2.2 BMS with BIM

BIM is used as a multi-dimensional building facility information database (Chuck Eastman, 2008). It provides structured information management solution throughout the whole building lifecycle (National Institute of Building Sciences, 2007). It is capable of improving the fragmented data (K. P. Kim & Park, 2016). Meanwhile, BIM has the capacity for nD simulation and analysis (GhaffarianHoseini, Zhang, et al., 2017). Towards this end, numbers of researchers begin to use BIM models to bridge the gaps between BMS and data analysis, and BMS and structuring (Becerik-Gerber et al., 2012; H.-M. Chen, Chang, & Lin, 2016; T.-W. Kang & Choi, 2015; A. Oti et al., 2016). However, most of the projects only scrape the surface of BIM, and these projects fail to take full advantage of nD BIM capacity for BIM-BMS integration (McCartney, 2010).

The main problem of this phenomenon comes from unstandardized modeling outcomes (Zadeh, Wang, Cavka, Staub-French, & Pottinger, 2017). Firstly, some BIM models need to be detailed/developed. Most of the existing BIM models were made without considering post-construction use at the early stage (A. Oti et al., 2016). According to BIM Forum (2016), the requirements of the level of details vary from LOD 100-LOD 500 in the building lifecycle stages. Normally, the O&M phase requires the highest level of details than other stages (Becerik-Gerber et al., 2012). A lack of details in the BIM model leads to a superficial integration between BIM and BMS.

Secondly, BIM models need to be simplified into a lightweight model. A representation system is needed for BMS-BIM integration in the O&M phase (Plesner & Horst, 2013). However, the daily use system might be limited to hardware capacity (Johansson, Roupé, & Bosch-Sijtsema, 2015). Raw BIM models in both the design stage and construction phases can overload the representation system (Liu, Xie, Tang, & Jia, 2016; Plesner & Horst, 2013). This urgent the need for a more specific BIM model.

Besides, non-standard modeling process decreases the accuracy of information. Leaky BIM models, which are not satisfying the standard, block the efficient use of BIM models (Becerik-Gerber et al., 2012).

Furthermore, unable to access all parts of a BIM model leads to the limited use of information (Solihin, Eastman, & Lee, 2016). The most likely cause of the inaccessibility is information being stored on multiple servers with incomplete access (East & Brodt, 2007). Without a federated BIM model, facility information might be fragmented. Fifthly, lack of timely updates in BIM causes the miss of consistent information. The quality of construction as-built BIM handover can have a profound consequence on the information consistency (East & Brodt, 2007). However, this handover process is usually unstandardized (Bayar, 2016). Above all, currently pairing with unstandardized BIM models leads to the limited practicality of current BMS systems.

3.3 Global Suggestions

By reviewing the literature, suggestions in the global context were collected. Those solutions can be categorized into five main groups: BAS, BDS, KBS, BPS. The history and evolution of these five will be explored in the followings.

3.3.1 Building Automation Systems

Building automation has a very long history (Kisačanin & Agarwal, 2001). Cornelus Drebbel (1572-1663) invented a U-shaped vessel housing mercury. It was a temperature sensor which operated a lever arm that ultimately controlled heat output by using a draft to a furnace through a mechanical linkage (S. Bennett, 1996). Later, Rene-Antoine Ferchault de Reaumur (1683-1757) invented the Reaumur Scale Thermometer, based on Drebbel's concept. De Reaumur also projected the idea for thermal control of incubators (Greydanus, Feinberg, & Merrick, 2015). These efforts were further improved due to works on automatic control of steam engines. During the 1800s, automated control systems included temperature, pressure, liquid level and rotating machinery. In 1871, Maxwell (1831 – 1879)'s textbook titled "Theory of Heat" and his work "On Governors" followed the same direction (Sarkar, Salazar-Palma, & Sengupta, 2010). With access to electricity in the 1900s, significant improvements were made. Elmer Sperry, in 1911, invented the gyroscopic compass and utilized a PID system for automated ship steering. In 1914, Edgar Bristol developed pneumatic flapper nozzle amplifier to control devices on a binary on-off mechanism (S. Bennett, 1996).

With the advent of computers and electronic control systems, direct digital controls minimized the number of moving parts linked with pneumatics and control loops while enhancing efficiency. Early computer-controlled systems were also used for semi-automation. Application of computers for complete control systems was initiated by Imperial Chemical Industries in collaboration with Ferranti for soda ash plant direct logic control at Lancashire in 1959 where 200 computers processed 256 input measurements and 120 loops (Aylen, 2010). Initial Building Management Systems in the 1960s and 1970s used air-based pneumatic controllers incorporating regulators, valves, actuators, sensors, petitioners, and controllers to operate HVAC systems (Kastner, Neugschwandtner, Soucek, & Newman, 2005). During this period, Direct Digital Control computers were extensively used by Industrial-type companies to improve their return on investments (Arahal, Barrero, Ortega, & Martin, 2016).

After the 1970s' advancements in microelectronics and software packages, more robust and reliable building automation systems emerged (Levermore, 2000). Remotely monitored and adjusted lighting, water, and temperature systems were introduced in the 1990s (McGowan, 1995). Besides, the term “Energy Management System” was coined to explain the monitoring, control, and optimization of building energy systems during this period. The term “Smart Building” was also conceived for addressing centrally controlled processes allowing facility managers to manipulate hardware and software linkages to control lighting, escalators, plumbing systems, security systems and boilers (H. Chen, Chou, Duri, Lei, & Reason, 2009). In recent years, construction companies utilize pre-mounted controlled hardware for advanced controls whereas older buildings are fitted with bridging controls allowing application of an interface with pneumatic systems to work with digital systems (Huang, Lu, & Chen, 2017). “Smart Grid” is being evolved comprising real-time power reporting and advanced building monitoring system. Efficient communication of these systems with power providers warrants energy responsive, efficient and environmentally sustainable buildings (Güngör et al., 2011).

Currently, there is a trend for utilizing advanced techniques to embrace BMS data, such as BIM, KBS, Internet of Things (IoT), Big Data Analysis, Data Mining, and Cloud Computing. The framework for integrating BMS data with BIM has been developed by A. H. Oti et al. (2016). Pärn et al. (2017) established a workflow for knowledge retrieval for BMS in a BIM environment. At the same time, as presented in this research, an integration of BIM, BMS, and KBS has been put forward by GhaffarianHoseini, Zhang, et al. (2017).

Linder, Vionnet, Bacher, and Hennebert (2017) proposed to manage the “Big Building Data” to increase the cooperation capacity while Capozzoli, Piscitelli, Gorrino, Ballarini, and Corrado (2017) attempted to reduce the energy consumption of HVAC systems by data analysis.

Capozzoli, Piscitelli, and Brandi (2017) utilized data mining for typical load profiles in buildings to support BMS process; Terroso-Saenz, González-Vidal, Ramallo-González, and Skarmeta (2017) put the BMS onto IoT platform and optimize the data mining and analysis process. L. Wang, Ma, Yan, Chang, and Zomaya (2018) have researched on addressing issues in using Cloud Computing in BMS. Similarly, Plageras, Psannis, Stergiou, Wang, and Gupta (2017) have surveyed how to combine those techniques in BMS, including Data Mining and Cloud Computing.

In all the studies reviewed here, BMS is recognized as potential to be extended to further function by the integration with other advanced techniques. BMS itself keeps monitoring and controlling for all the building systems while IoT makes this management onto the internet. However, both BMS and IoT suffered from the lack of data analysis which raises the demand for data mining (Lin & Yang, 2019). At the same time, BIM provides an objective-oriented data structure to cut off significant monitoring and control data issues for them as well as a right environment for data mining (Z. Pezeshki, Soleimani, & Darabi, 2019). Meanwhile, KBS builds a suitable environment for the information retrievals. However, BIM models take a big space for hardware story and usually overload the Central Processing Unit (CPU) while cloud computing provides shared pools of configurable resources which allows the users to focus more on their facility management works instead of deploying the hardware (Redmond et al., 2012).

3.3.2 Building Description Systems

BIM originated from BDS which was proposed by Eastman in 1974 (C. F. Eastman, David; Lafue, Gilles; Lividini, Joseph; Stoker, Douglas; Yessios, Christos, 1974). BDS was used to store and update building information to cater for design alterations. In 1986, the term “Building Modelling” was first used by Aish (1986), five years before acknowledgment of the term “Building Information Model” by G. A. van Nederveen (1992). In 2002, Autodesk inc (2002) released a white paper titled “Building Information Modelling”, introducing the concept of BIM, its definition, characteristics, benefits, and roadmaps.

In 2006, Associate General Contractors of American (AGC) (2006) initiated promoting BIM through releasing and adopting BIM guidelines and standards. This was a major starting point for the development of BIM guidelines and standards to become internationally widespread. Among these are NBIMS-US V1 (2007) , NBIMS-US V2 (2012) and NBIMS-US V3 (2014), released by Building SMART alliance™, BS 1192:2007 published in UK, which was then superseded by BS 1192:2007+A1:2015 (bsi., 2013), along with BB 1192-2:2013 (bsi., 2013), BB 1192-3:2014 (bsi., 2014), and BB 1192-4:2015 (bsi., 2015). In 2013, BIMForum finished the first version of the Level of Development Specification and standardized the process of BIM projects (BIMForum, 2013), which was amended later in 2015 (BIMForum, 2015).

BIM level 2 was achieved in 2016, as planned by the UK government. Efficient application of BIM is critically dependent on the development of IT/software technology (Bouška, 2016). In the same year as AutoCAD v1.0 being released (Lambert, 1982), ArchiCAD was first introduced in 1982. It was followed by the release of Radar CH (ArchiCAD 1.0) in 1984 (Lincoln H. Forbes, 2010). Bentley Systems (2016) was also founded in 1984 followed by the release of MicroStation 1.0 1985. Charles River Software was founded in 1997. It was then renamed Revit Technology Corporation when releasing Revit 1.0 in 2000. Next, Autodesk purchased Revit Technology Corporation in 2002 and published the first BIM white paper (Autodesk inc, 2002).

Since then, various BIM solutions are offered mainly by Autodesk, Bentley Systems, and Graphisoft (Laiserin, 2003). Other BIM solutions such as Dassault Systems (founded in 1975), which developed CATIA in 1977 as an indoor development tool, and Gehry Technologies (established in 2002), where Frank Gehry developed Digital Project in 2005 based on Dassault Platform, also played important roles (Frausto-Robledo, 2013). Since then, those software were frequently updated, especially Autodesk Revit which normally updated yearly.

As mentioned above, more and more software BDS solutions began to be used by the project end users for various purposes. Despite this, each solution usually produces its own format for data story which obstructs the data exchange (Autdesk Inc., 2018; Bentley Systems, 2016). To maintain the interoperability among various software solutions, Industry Foundation Classes (IFC) protocol was agreed on by most of the AEC software solution provider. The development history of IFC was started in 1997 when IFC 1.0 was released by buildingSMART (buildingSMART International Ltd., 2018). Since then, IFC 2x to 2x2, IFC 2x3 have been used till 2014 before IFC 4.0 was adopted. IFC 4.0 updated the definition of space boundaries which is capable of supporting energy calculations and advanced simulations. Wherein thermal boundaries are involved as a special subtype with direct reference to the opposite boundary and inner boundaries. The application of IFC always attends to support the data exchange requirements.

3.3.3 Knowledge-Based Systems

Knowledge management (KM) was then introduced in 1991 (Thomas, 2016). In 1994, the International Knowledge Management Network (IKMN) was released online (Thomas, 2016). In 1995, KMS received increasing attention when the European Community began offering to fund for KM-related projects (Thomas, 2016). In 2004, feature construction methodology was proposed facing new attributes in the KBS (Piramuthu, 2004). This method mainly reduces data dimensionality and improves prediction performance (Sondhi). KMS were also widely used in railway scheduling (Te-Wei Chiang, 1998), manufacturing (Özbayrak & Bell, 2003), maintenance planning, space transportation (Ruiz-Torres, Zapata, Nakatani, & Cowen, 2006), health sciences (Begum, 2011), and AEC/FM industry (Motawa & Almarshad, 2013). In 2015, a knowledge-based expert system for assessing the performance level of green buildings was developed, which marks the application of the knowledge-based system and the case-based reasoning in green buildings (Nilashi et al., 2015).

One of the most important part of a typical KBS is the reasoning algorithm. Among those reasoning algorithms, CBR is an Artificial Intelligence (AI) approach to reasoning and learning from historic experiences (Plaza, 1994). It originated from the research of Roger Schank at Yale University in the early 1980s. Schank's model (Schank, 1982) of dynamic memory was the rudiment of CBR systems. Janet Kolodner's CYRUS (Kolodner, 1983) and Michael Lebowitz's IPP (Lebowitz, 1983) were applied and regarded as the earliest CBR systems. A number of AI and expert systems were developed during 1980-1990, such as KB-Reducer (Ginsberg, 1988), the "M" directory (Indiana University, 2016), the Rule Checking Program for the ONCOCIN expert system (Suwa, 1982), CHECK, ARC, and EVA5, Rob Acksyn's and Don McCracken's Knowledge Management System (KMS) (Thomas, 2016).

3.3.4 Building Performance Simulation Systems

Developing building automation systems has become the focus of researchers since the early 1960s (Mitalas, Stephenson, & Baxter, 1960). The use of an analog computer for building air-conditioning calculations was developed by Mitalas in 1960 (Mitalas et al., 1960). A group of mechanical engineers then formed the Automated Procedures for Engineering Consultants (APEC) in 1966 marking the first significant instance of using computers in the design and analysis of building systems (T. Kusuda, 1970). APEC, in 1967, developed the program APEC Heating and Cooling Peak Load Calculation (HCC) to measure the hourly peak and annual heating-cooling loads for heating, ventilating, and AC (HVAC) (APEC, 1967).

In 1969, the American Society of Heating, Refrigeration, and AC Engineers (ASHRAE) Task Group on Energy Requirements (TGER) published the procedures for simulation, the performance of components and systems for energy calculations (Stoecker, 1975). The first ever international building performance simulation conference was organized in the USA in 1970, with 62 papers by authors from 11 different countries expressing future expectations in this field (Hensen, 2000). When the published procedures became accessible to engineers, the General American Transportation Corporation was commissioned by the U.S. A computer program was developed for analysis of energy utilization in postal facilities based on Response Factors Method and Weighting Factor Method (Lockmanhekim, 1971). This is known as the first public domain energy analysis program, called the "Post Office Program" (Lockmanhekim, 1971).

In 1972, Trane Air Conditioning Economics was released for load and energy calculations (Weilun Lee1, 2015). Post office Program was then merged with the National Bureau of Standards Load Determination program to develop a life-cycle cost analysis of building components (Tamami Kusuda, 1974). Based on the development of the Post Office Program, the NASA Energy Cost Analysis Program was developed and released by the National Aeronautics and Space Administration (NASA) in 1975 (Henninger, 1975). During the same year, procedures for determining the heating and cooling loads for computerizing energy calculations along with procedures for simulating the performance of components and systems for energy calculations were proposed (Henninger, 1975; Sun, 1976).

Transient Systems Simulation Program was developed by Solar Energy Laboratory, the University of Wisconsin-Madison for building energy simulation programs, solar thermal simulations, and photovoltaic analysis during this era (dos Santos & Mendes, 2004). In 1977, the Energy Research and Development Administration and the California Energy Commission upgraded NECAP and renamed it CAL-ERDA (Tupper et al., 2011a). Shortly after that, CAL-ERDA User's manual and Program manual were introduced (G. A. Bennett & Hunn, 1977; Graven & Hirsch, 1977). Simultaneously, the U.S. Army Construction Engineering Research Laboratory released the Building Loads Analysis and System Thermodynamics program which was initially able to model some basic building systems and later multiple zones (Tupper et al., 2011b).

In the following year, 1978, the U.S. Department of Energy introduced DOE-1 (a slightly enhanced version of CAL-ERDA) (Leighton et al., 1978). A decade later, the Hourly Analysis Program was released by Carrier for load and energy calculations (Weilun Lee1, 2015).EnergyPlus was developed in 1996 and then was first released in 2001, funded almost exclusively by USDOE (Crawley et al., 2001; Weilun Lee1, 2015). It was facilitated with enhanced features compared to previous building simulation software namely BLAST and DOE (Weilun Lee1, 2015). Subsequently, other major building performance assessment/simulation software (IES VE) 3.0 (Tupper et al., 2011b) and GreenBuilding XML (gbXML) were developed in 1998 and 1999 respectively. This key building simulation software has constantly been under update and development. An update track can highlight TRACE 700 (full version) in 2001 (Tupper et al., 2011b), DOE-2.1e-121 in 2003 (Tupper et al., 2011b), TRNSYS v17 in 2010 (Tupper et al., 2011b), Revit Conceptual Energy Analysis in 2010 (Tupper et al., 2011b), eQUEST 3.65-7163 (eQUEST, 2016), VE 2015 Pack 2 (IESVE, 2016), HAP v4.91 (Carrier, 2016), EnergyPlus 8.5 (EnergyPlus, 2016)

3.3.5 Fault Detection and Isolation Systems

In the past four decades, massive advances have been made in the discipline of process control (Venkatasubramanian, Rengaswamy, Yin, & Kavuri, 2003). Wherein, there are two types of controls: regulatory control and non-regular control. In the regulatory control mode, valves, motors, and pumps are simply opened and closed. By contrast, the non-regulatory control systems such as distributed control and model predictive control systems work in a more complex way.

With the rapid development of automation technology, the regulatory control was automated using computers (Frank, 2019; Kletz, 1999). Provided that, manual activities remain as an essential task towards responding to abnormal events in both control mode. Towards this end, an Abnormal Event Management (AEM) was identified as a key component of the supervisory control (Ariamuthu Venkidasalapathy, Mannan, & Kravaris, 2018). As a key technology that can facilitate AEM, Fault Detection and Isolation (FDI) is commonly used for a more complex control. In the past decades, process history was analyzed by FDI methods to maintain efficient use of control system (Beghi, CecChinato, Corso, Rampazzo, & Simmini, 2013). Provided that, the FDI methods should be highly responsive to the malfunctions. However, responsiveness and tolerable performance conflicts in operation (Willsky, 1976). Considering the algorithms available during the past decades, tolerable performance was emphasized more. To put it into another way, a history-based method was more popular adopted. Despite this, the responding time will be largely reduced. With the fast development of AI algorithms, real-time FDI methods were promoted (Gajjar, Kulahci, & Palazoglu, 2018). To maximize the tolerant performance for an FDI method while remaining the responding time becomes a hot topic in today's academic studies.

3.4 Evolution of Technologies

More recent attention has focused on the provision of sustainability for the buildings throughout its whole lifecycle (Oviir, 2016). Within such a lifecycle, the operation phase holds the longest duration along with the highest costs for management and maintenance

(BCPP, 2016). Hence, to facilitate the building sustainable performance in the operation phase plays a more crucial part than in the other phases.

With that end in view, numbers of research have been examined to engage a BMS for managing FM activities throughout the operation phase (Ippolito et al., 2014). In order to perform high energy efficiency, BMS was used for building facilities smart monitoring and control (Kučera et al., 2013). Such a system provides a visualized interface for energy consumption profiles, which benefits the O&M staff (A. Oti et al., 2016). For the non-expert staff, the historical energy performance within such system provides an inclusive understanding of energy use.

However, several studies have revealed that the traditional BMSs suffer from the lack of data analysis and structuring (A. Oti et al., 2016). Without analysis, raw data are fruitless. Abuse use of BMS for reporting fragmented data fails to add value to the post-construction performance (Molina-Solana et al., 2017). Meanwhile, the unstructured data streams frustrate the end users by its overwhelming amount (Fan et al., 2015). Hence, recent literature suggested that traditional BMSs are limited to promoting post-construction sustainability.

With this in mind, BIM emerges to be a potential solution. Many researchers have utilized BIM as a multi-dimensional (nD) facility information repository, such as Chuck Eastman (2008), Love et al. (2014), and Dong et al. (2014). Refer to National Institute of Building Sciences (2007), such repository can efficiently structure the lifecycle information. K. P. Kim and Park (2016) indicated that BIM enables the streaming of fragmented data within a structured framework. Together these studies indicate that BIM assists the processes of simulation analysis (GhaffarianHoseini, Zhang, et al., 2017). To that end, previous studies of BIM have attempted to use BIM models for bridging the gaps between BMS and data analysis and structuring (Becerik-Gerber et al., 2012; H.-M. Chen et al., 2016; T.-W. Kang & Choi, 2015; A. Oti et al., 2016).

Up to now, a number of studies have revealed that the unstandardized modeling processes largely limit the effectiveness of involving BIM (Zadeh et al., 2017).

First, almost all the BIM models were established without the consideration of the end users at the early stage (A. Oti et al., 2016). Referred to BIM Forum (2016), the requirements of the modeling outcomes vary from LOD (Level of Development) 100-LOD 500 throughout different building lifecycle phases. Another key thing to remember, the operation phase requires the highest LOD among all phases (Becerik-Gerber et al., 2012). Yet, a lack of details in FM model leads to a superficial integration between BIM and BMS.

Then, the BIM-enabled BMS might be limited to hardware capacity (Johansson et al., 2015). Raw BIM models created in both design and construction phases easily overload such a representation system (Liu et al., 2016; Plesner & Horst, 2013). With this in mind, BIM models should be simplified into a more lightweight model.

Next, existing literature suggested that a lack of standard modeling process reduced the accuracy of information (Becerik-Gerber et al., 2012). Besides, due to the non-fully cooperation in the design and construction phases, the end users might not be able to access each part of a BIM model (Solihin et al., 2016). East and Brodt (2007) indicated that the data were possibly stored on various servers with limited access. If such BIM is not federated, facility information is still fragmented.

Last, a lack of maintenance of FM BIM models causes information inconsistency. Not to mention, the construction handover processes for BIM were not standardized (Bayar, 2016).

Above all, integrating an unstandardized BIM model, current BMS practices are still limited in data analysis and structuring. Towards promoting building intelligence in New Zealand, these findings rose an urgent need to bridge the gaps in integrating BIM and BMS.

To find the potential solutions for our aim, several specific techniques were reviewed, including supervisory control and data acquisition (SCADA), computer graphics, and database. At first, SCADA systems collect any available data from the systems they monitor and control (Peharda, Ivanković, & Jaman, 2017). Refer to Rezai, Keshavarzi, and Moravej (2017), the SCADA plays an essential part in modern infrastructures, such as built environment (Figueiredo & Sá da Costa, 2012), smart grids (Sayed & Gabbar, 2017), smart factory (S. Park, 2016). Massive researchers have identified the development of such a technique and divided into four generations: monolithic (Banach, Zhu, Su, & Wu, 2014; Kacprzyk & Kępa, 2014; Sani, Linderhed, & Sandberg, 2018), distributed (Dulău, Abrudean, & Bică, 2015; Figueiredo & Sá da Costa, 2012; Salihbegovic, Marinković, Cico, Karavdić, & Delic, 2009), networked (Finogeev & Finogeev, 2017; McClanahan, 2002; Rezai et al., 2017), and object-oriented which is also known as IoT (Afzal, Umair, Asadullah Shah, & Ahmed, 2017; Bergesio, Bernardos, & Casar, 2017; Lindley, Coulton, & Cooper, 2017).

Secondly, computer graphics technology assist the developers with digitally synthesizing and manipulating visual content. With the fast development of such technology in nowadays, the way in which graphics are used and perceived has been changed (Liang, Sit, Chang, & Zhang, 2016). At an early time, pixel-based tools were used for symbolization (Bouvier, 2002). Rather than presenting accurate graphs, these tools were capable of giving schematic illustrations. Then, vector-based tools, typically (Computer Aided Design) CAD, were introduced to make those graphs more accurate (Mikolajczyk, Latos, Paczkowski, Pimenov, & Szynka, 2018). When it comes to the BIM era, entities became object-oriented (Ghaffarianhoseini, Tookey, et al., 2017). To put it in another way, the computer graphics tools trend to be more and more realistic.

Last, database technology has played a more and more integral role of modern business (Lockemann, Kemper, & Moerkotte, 1991). Capable of being retrieved by a program, a database is a structured collection of records/data stored in a computer (Berrington, 2017). It consists of numbers of tables comprising records (rows) and fields (columns), which contain data values. Prior studies have identified three groups of the database: flat files database (Berrington, 2017), navigational database (Takizawa, Itoh, & Moriya, 1987) or relational database (Maier, 1983), and object-oriented databases (Fairfield, 2004). To give an illustration, the evolution of computer graphic, SCADA, and Database techniques paired with their interaction was given in Figure 3. All things considered, the integration of BIM and BMS mentioned before is located in the orange areas; while the adoption of IoT-enabled BIM-based BMS can deliver a higher building intelligence.

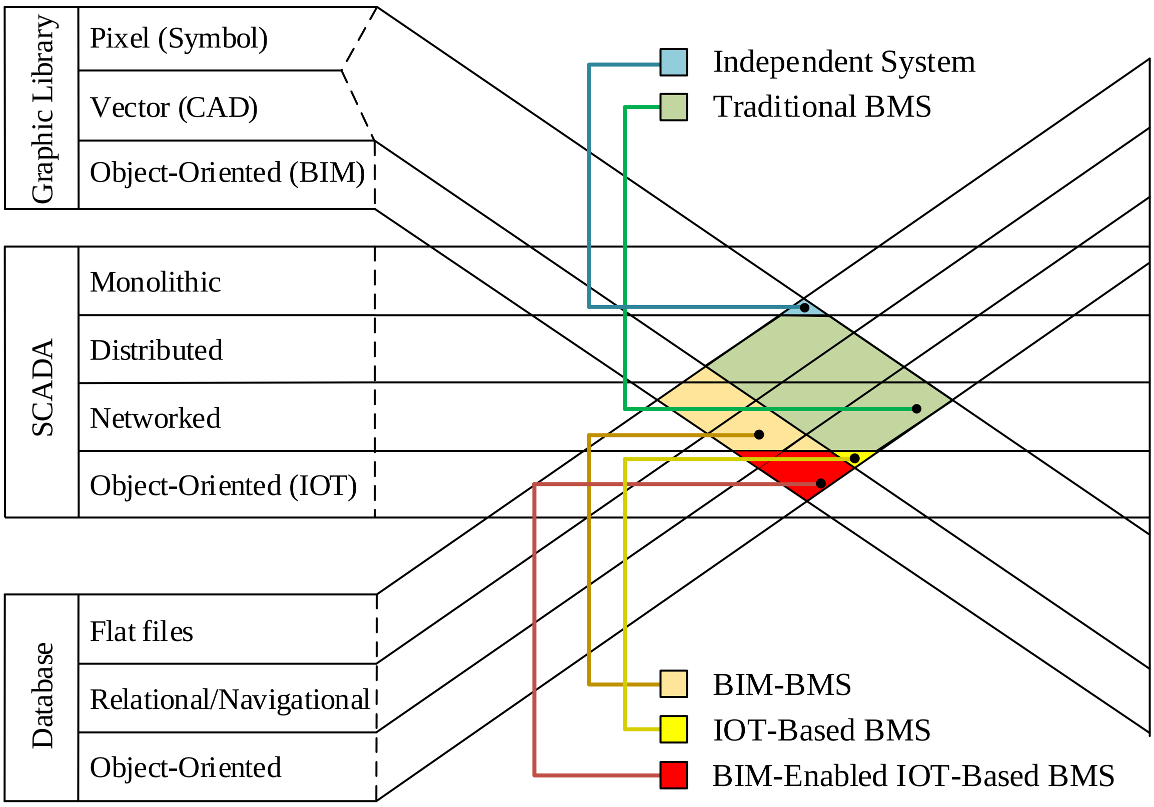


Figure 3 Evolution of Techniques.

3.5 Current BIM Evaluation Methods

Currently, the evaluation methods for the post-construction BIM applications all over the world are still with cognitive limitations. After a review of the last decade publications, we found that most of the research methods are too descriptive. Some of them were merely reviewing the literature while the others made more or less disguised displacement of another field. Most commonly, BIM was mentioned in publications merely with the purpose of improving the novelty of the existing knowledge.

In order to avoid making the research too subjective, numbers of researchers adopted interview methods paired with both qualitative and quantitative analysis. However, these researches still went with visible limitations.

For instance, NBS (2013) carried out an international BIM survey among UK, Canada, Finland and New Zealand. As mentioned before, New Zealand BIM adoption is still at a disadvantage. However, the results show that New Zealand was higher in responding currently using BIM (57%) while the UK (39%). The awareness of BIM in New Zealand was the highest than other three countries (98%). It is no doubt that the researchers in NBS conducted the survey rigorously. However, the uncertainty in the respondents can sometimes reduce the accuracy of the research. NBS carried on a quantitative research for evaluating those BIM projects. They adopted the fixed-point survey, which is one of the most frequently adopted methods. They used this method to evaluate whether a BIM-based system was helpful for a particular purpose in a quantitative way. Respondents were asked for few questions about the satisfaction with the proposed system by using scales or scores. However, respondents have a very limited capacity for retrieving implicit thoughts explicitly, and the responses were highly biased in favor of their own benefits (Woodside, 2010).

In a BIM-FM integration case study, T.-W. Kang and Choi (2015) conducted a round of interview with the facility management staff to evaluate the performance of the BIM-based FM system. The indicator used in this research was the average cost-saving. It comes from the expected time-saving which is calculated from that the saved times the average hourly wage. However, the expected time resulted from the interviewees' oral answers. There is a fact that fewer people would like to rebuke his or her own works in a survey. This makes the indicator results out of the tolerance. Although some research adopted the same indicator by direct observation, the efficiency improvement is still overestimated without considering the Hawthorne Effect. Hawthorne Effect refers to the unintended influence of observers (Kurtz, 2017). The observation activity itself improves the work efficiency of the staff. Therefore, evaluating post-construction BIM becomes a contemporary issue.

A possible explanation for above inconsistency might be that BIM is an amplifier in its nature; it can facilitate more than 126 AEC applications, however, can hardly be used alone. This leads to that no suitable indicators can objectively evaluate BIM. Rather than evaluate BIM directly, this research prefers to evaluate the impact on facility management performance by adopting BIM. However, as mentioned before, the Hawthorne Effect can influence the results of the observation. Adjusting this bias is essential to improve the accuracy of the results. To minimize the Hawthorne Effect, disguised observation should be used throughout the whole observation process. In disguised observation, respondents are unaware of that they are being observed and thus behave naturally (Baltimore County Public Schools, 2017). Disguise is achieved by disguising as self studying.

As for building performance evaluation, this research focuses on facility management performance, covering facility operation and maintenance. Instead of predicting the future performance, this research focuses on the lagging results. Lambe (2016) listed three main metrics for past facility management performance:

(1) Hot/cold calls per building occupant;

(2) Building energy use by month;

(3) A number of emergency repairs as % of total equipment work orders.

In this research, those three metrics have been translated into three indicators: energy efficiency, occupant thermal comfort, and facility maintenance-saving. Regarding facility management performance, a literature review was conducted of studies that what is the existing evaluation for energy efficiency, occupant thermal comfort, and facility maintenance-saving. Instead of inaccurate indicators for BIM, many indicators in those fields have already been validated (Lynch & Mosbah, 2017; Twardzik et al., 2019).

In the first place, the energy efficiency depends on the environmental impact and energy benchmark. In the latest years, Building Lifecycle Assessment (LCA) became a hot topic. A very comprehensive assessment of environmental impacts considering the product’s life from the cradle to the grave is made in LCA. Numbers of existing research shows that energy consumption benchmark E_T (kWh/m^2/year) was selected as one of the main indicators in LCA (Muñoz, Morales, Letelier, Muñoz, & Mora, 2017). It was also used in Citherlet and Hand (2002) for assessing the energy consumption. Meanwhile, Ghose, McLaren, Dowdell, and Phipps (2017) listed twelve environmental impacts including CO_2, CFC-11, C_2H_4, SO_2, PO_4, and Sb emission (eq/m^2/year). Also, payback period (years) was suggested by Environmental Protection Authority (2008) cited in Ghose et al. (2017). On the other hand, assisted by IES VE, Ecotect and Greenhouse Studio, Dynamic Simulation Modelling (DSM) was conducted in many calculation systems. DSM was adopted in Technical Memorandum 54 (TM54) to calculate the predicted energy consumption (kWh). Also, in two model method of Green Star, DSM is used to calculate both the energy use benchmark and the environmental impact (kg CO_2/m^2) for education & industrial buildings. In two model method, two models are calculated: actual building model and reference building model. Comparing to the reference values, the actual performance can be evaluated. However, this method strongly needs a sensitivity analysis, as few research reflect that sometimes the outcomes are underestimated.

Secondly, the occupant thermal comfort mainly evaluated by two kinds of methods: Vote and Feedback, and Psychometric Chart method. In the literature, there are many vote and feedback formulations. Among them, the Predicted Mean Vote (PMV) and the Actual Mean Vote (AMV) are one of the most popular and the simplest ones (X. Chen, Wang, & Srebric, 2015). This research selects PMV, as it will make less interruption to the participants while faster the data collection process (Broday, Moreto, Xavier, & de Oliveira, 2019). PMV is based on direct observation while AMV is to conduct a survey. Obviously, AMV will take longer time. On the other hand, Predicted Percentage Dissatisfied people (PPD) method is more complex in its regression (Q. Chen, 2004). It has six parameters: air temperature, radiant temperature, air speed, humidity, occupant clothing, and metabolic (Pritoni, Salmon, Sanguinetti, Morejohn, & Modera, 2017). Alternatively, Psychometric Chart method is more accurate. The Psychometric Chart is a graphic representation of the relationship between air temperature and humidity. A comfort zone is defined in Psychometric Chart both in winter and summer by Stefano Schiavon (2014). BMS is then used for monitoring the operational temperature and humidity. Then take the integral of all the compliance operation time and result in the total compliance operational time. To minimize the influence from season shifting, adaptive thermal comfort model has also been used. This should be used to adjust the results of the integral of compliance operation time. Terrill and Rasmussen (2016) proposed to combine the PMV method and the Psychometric Chart method to optimize HVAC system for maximizing the energy efficiency while remaining the occupant comfort.

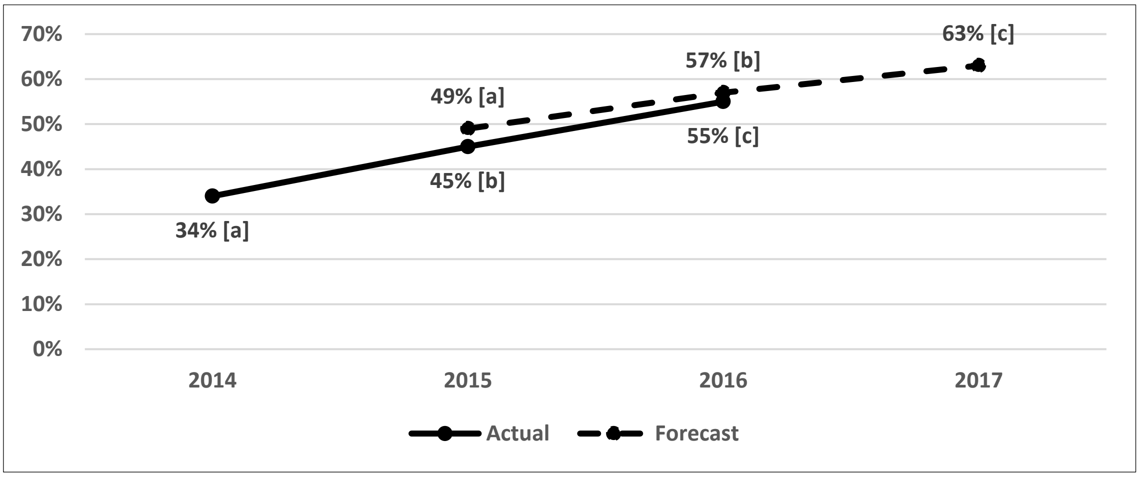
Thirdly, to investigate the maintenance-saving is the most complex. Take T.-W. Kang and Choi (2015) for example, most of the researchers in this field adopted interview method based on a salary saving indicator. However, they evaluated the effectiveness of BIM superficially. They propose to create a maintenance method which will be used. It has two sub-indicators, maintenance savings, and risk prevention. Once an asset is installed, occupants would start to use it. There are two maintenance measurements: warranty use frequency and maintenance cycle. BIM platform can be used to inspect the actual use frequency and record the use lifetime of the asset as well. Inspecting out of warranty use asset can prevent risks while inspecting less used asset can reduce replacement costs. Measurement of these two indicators can efficiently evaluate the post-construction BIM uses.

Therefore, this research should focus on evaluating BIM-BMS integration with the building performance it affects, such as building energy efficiency, occupant thermal comfort, and maintenance-saving. Considering the research scope, only energy efficiency was evaluated at this time, while future study will focus on the rest ones.

3.6 BIM adoption in New Zealand

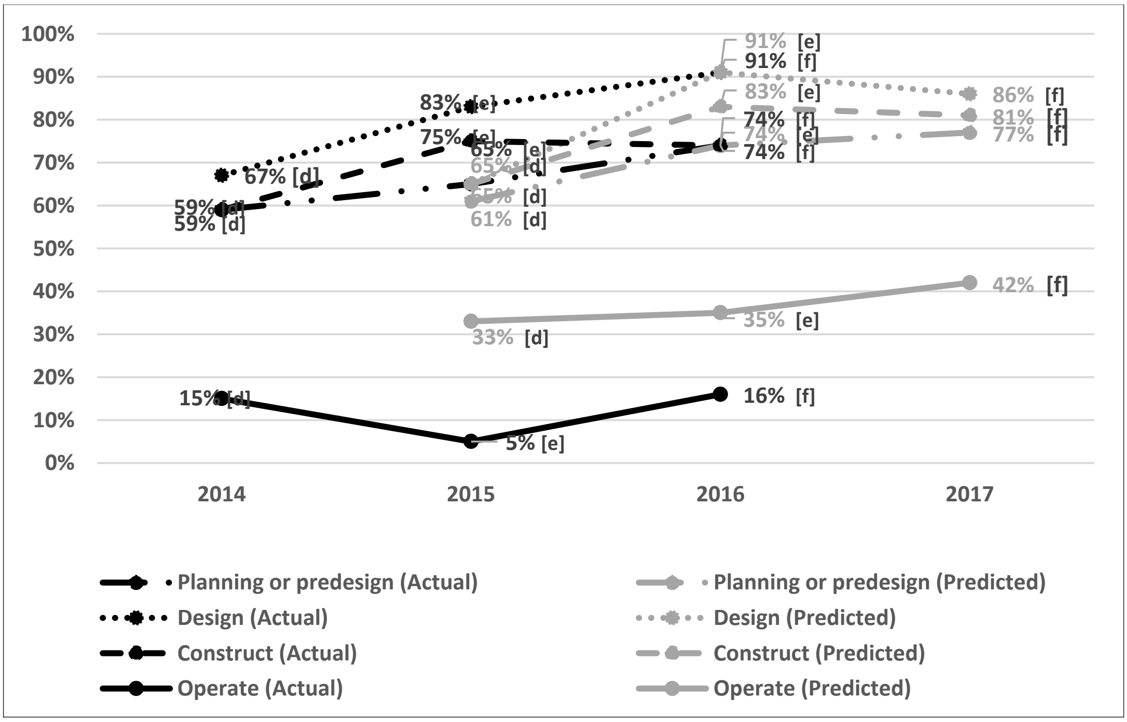
Recently, many countries mandated BIM, especially in the UK. BIM Task Group (2011) classified BIM maturity into four levels and set a goal for the UK AEC industry to achieve BIM level 2.0 by 2016. At BIM level 0, 2D Drawings and non-graphic documents are used for coordination; at BIM level 1.0, limited 3D techniques have been used for information sharing; at BIM level 2.0, a federated BIM model is adopted to integrating all the separate, distinct discipline models, however, at this level, the BIM model still cannot flow throughout the whole building lifecycle; at BIM level 3.0, the information delivery from BIM use will be able to be shared throughout the whole building lifecycle and with all the stakeholders. However, BIM Level 3 is too complex to achieve, and only a few leading companies in the international AEC industry have made some attempts to do it (Alreshidi, Mourshed, & Rezgui, 2017).

In contrast, the New Zealand government decided on promising BIM by supporting accelerating activities rather than mandating BIM (BCPP, 2016). This lead to a lower adoption rate than the UK and other countries who are mandating BIM and New Zealand AEC industry is still aiming for BIM level 2.0 (BIM Industry Training Group, 2016). Nevertheless, BIM acceleration activities have resulted in positive outcomes. Eboss has conducted BIM surveys in New Zealand. In their reports, as Figure 4 shows, there is a steady rise (approximate 10%) in BIM adoption since 2014, and it is expected to reach 63% in 2017. In recent years, BIM is embracing used in building planning, design, construction, and reached a rate of adoption for 91%, 74%, and 74% respectively at 2016 (See Figure 5). However, rare BIM adoption in post-construction lifecycle becomes a barrier to achieve BIM level 3.0. As Figure 5 shows, BIM adoption rate in the operation phase is 15% in 2014, 5% in 2015, and 16% in 2016. What was worse, the predicted adoption rate from the previous year was overestimated 28% in 2015 and 19% in 2016. A possible explanation for this might be that people in AEC industry urgently need it, but fewer people can do it. What’s worse, a potential bias toward higher BIM adoption for this research cannot be ignored. As an online library of product catalogs from 219 of New Zealand's leading architectural product suppliers, Eboss cooperated with BIM Acceleration Committee and sponsored the research initiative. The increase in BIM adoption in New Zealand will improve the benefits of Eboss. Thus, the actual BIM adoption rate might be lower than stated in these surveys. In summary, two facts have been identified. Firstly, from a BIM adoption perspective, BIM in New Zealand is fast developing but still at a disadvantage. Secondly, BIM use in the post-construction phase is essential for a complete building lifecycle application to achieve BIM level 3.0, however, currently the weakest in New Zealand.



Source: [a]: Eboss (2014) ; [b]: Eboss (2015); [c]: Eboss (2016).

Figure 4 Percentage of projects using BIM in New Zealand (Actual vs forecast).

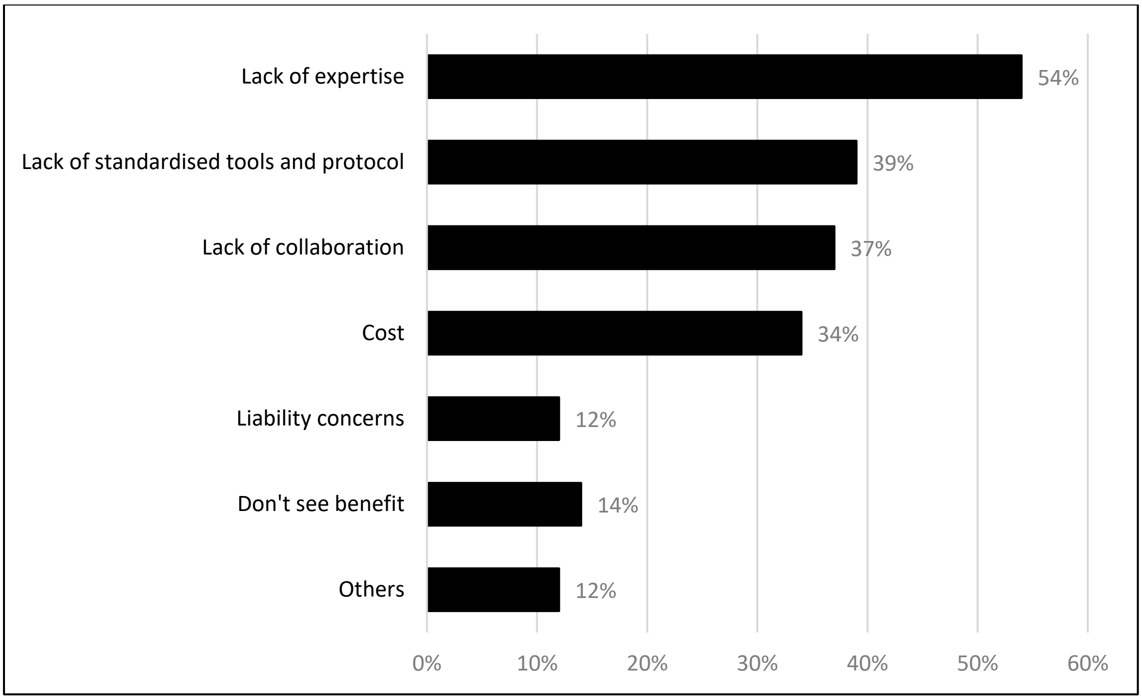


Source: [d]: Eboss (2014); [e]: Eboss (2015); [f]: Eboss (2016).

Figure 5 Industry BIM Use Across the Project Lifecycle.

In fact, the concept of BIM was established to embrace the whole building lifecycle. Involving BIM at the very beginning of a project can maximize the benefit of adopting BIM (The Building Intelligence Group, 2016). However, the O&M phase is near the end of a building lifecycle. Adopting BIM at this stage might obtain the lowest Return on Investment (ROI) since the model can only be used for O&M purpose while the requirement of post-construction BIM model is the highest among the building lifecycle.

This issue in cost could be one of the biggest barriers to BIM adoption in the O&M phase (See Figure 6).



Source: Clements (2014).

Figure 6 The Main Barriers to Using BIM in New Zealand.

Table 3 Estimate of Non-Residential Building Size Strata (2014).

Floor area strata	S1	S2	S3	S4	S5	Total*
Minimum floor area	5 m²	650 m²	1,500 m²	3,500 m²	9,000 m²	
Maximum floor area	649 m²	1,499 m²	3,499 m²	8,999 m²		
Approximate number of buildings	27,609	8,007	3,544	1,496	499	**41,154**
Percentage of buildings	67%	19%	9%	4%	1%	**100%**
Total floor area (million m²)	8.2	7.7	7.8	7.8	8.5	**39.9**
Percentage of floor	21%	19%	20%	19%	21%	**100%**
Average floor area (m²)	298	955	2,198	5,187	17,014	**970**

Source: Amitrano(Ed.) et al. (2014).

Table 3 shows that the number of existing nonresidential buildings in New Zealand is appropriately 41154 in 2014 which was mostly constructed before 2014. During that time, neither BIM survey nor BIM acceleration activities were made. This lead to the result that nearly no BIM models in those 41154 projects had been involved in the construction handover in New Zealand. The huge numbers of existing nonresidential building without a BIM model exacerbates the barriers to adopting BIM in an existing nonresidential building for O&M purpose. What worse, the lack of expertise in BIM plus the unstandardized BIM handover will also devaluate the BIM delivery. Also, without considering the post-construction application, the BIM model would be limitedly useful for O&M. Those two issues were regarded as the most mentioned barriers to BIM adoption (See Figure 6). Therefore, delivering a standard BIM model gradually since the very beginning stage is essential in promoting the BIM lifecycle application (BIM level 3.0).

An existing report recognizes the critical role played by a New Zealand BIM benchmark project in the O&M phase (BIM Acceleration Committee, 2017). However, there is little empirical data on BIM use in the O&M phase (Becerik-Gerber et al., 2012). Although BIM Acceleration Committee (2016) has released seven BIM case study reports, there is still a long distance from the benchmark level. Table 4 lists those seven BIM case studies in New Zealand. Only three of them involved BIM in the operation phase: UNITEC's integrated information system, Kathleen Kilgour Centre, and Wellington City Council Bracken Road Flats.

Table 4 BIM Lifecycle Applications in New Zealand.

Type	**Projects**	**I**	**II**	**III**	**IV**	**V**
Educational Buildings	Ara Institute of Canterbury Kahukura (AECOM, 2016)		X			
	UNITEC's integrated information system (Unitec, 2016)				X	X
	University of Auckland Undergraduate Laboratories (Beca, 2016)	X	X	X		
Medical buildings	Kathleen Kilgour Centre (The Building Intelligence Group, 2016)	X	X	X	X	
	North Shore Hospital's Elective Surgery Centre (Jasmax, 2016)	X	X	X		

		I	II	III	IV	V
Government Buildings	Christchurch Justice & Emergency Services Precinct (Ministry of Justice, 2016)		X	X		
Residential Buildings	Wellington City Council Bracken Road Flats (Wellington City Council, 2016)	X			X	

I: Pre-Design; II: Design; III: Construction; IV: Operate; V: Renovate.

Basically, Unitec (2016) is one of the early birds in exploring BIM use in the O&M phase. They first adopted the BIM-BMS integration in 2009, and 191 buildings had already been integrated with such system before 2016. They made a comparison of the annual electricity consumption (for two buildings) in three years. Unitec (2016) provided a statistical evaluation of the integration of BIM and BMS towards electricity savings. However, this case study had been unable to demonstrate how BIM makes many contributions to this saving. Also, the selected buildings are anonymous in this report, which means their characteristics are missing. Essentially, the tolerances from the fluctuations in actual occupancy and actual occupant behaviors cannot be ignored. However, these factors are not mentioned in this report. This case study would have been far more useful if Unitec (2016) had included a more rigorous evaluation.

Second, The Building Intelligence Group (2016) delivered an integrated 3D asset database from the BIM model of Kathleen Kilgour Centre. However, the evaluation is too descriptive, and no statistics are given for the O&M savings. Therefore, this case study fails to be a complete benchmark for the futuristic post-construction BIM use.

Last, Wellington City Council (2016) adopted BIM to manage their mass of data in Bracken Road Flats operations. Locating elements in BIM decreased the number of maintenance visit needed. However, they only provided the costs of BIM consultancy but not the benefits from BIM adoption. Limitations are that the scale of the selected project is too small, and it is just a residential project. NAHB (2016) (cited in Angelo Joseph

Garcia, Sinem Mollaoglu, and Syal (2016)) agreed that BIM is adopted mostly in complex and large-scale buildings instead of small or residential buildings. Small-scale residential BIM use cannot generalize to most of the BIM projects in the O&M phase. Furthermore, the research does not engage with residential buildings. Hence, this case study goes in a different direction. Considering all of this evidence, it seems that current post-construction BIM use in New Zealand has not yet been validated rigorously. Thus, New Zealand AEC industry might not have empirical data as a benchmark. This will make the future post-construction BIM investing into gambling and might reduce the adoption of BIM in O&M phase.

3.7 Current Research on BIM in New Zealand

Very little was found in the literature on exploring BIM in New Zealand. This reconfirms that New Zealand BIM is still early. In this regard, only four articles were obtained from the literature (See Table 5). The first two of them were developed by our research team; the third article examined the 5D BIM use in the construction phase; the fourth article was developed to promote the tertiary teaching by using BIM technology. In terms of the amount of research, there is an urgent need on researching BIM, especially in the post-construction phase. This has reconfirmed the significance of our research.

Table 5 Articles Mentioned BIM AND with Affiliations in New Zealand.

Titles	**Method**	**Phase**
Building Information Modelling (BIM) uptake: Clear benefits, understanding its implementation, risks and challenges (Ghaffarianhoseini, Tookey, et al., 2017).	Review	General
Application of nD BIM Integrated Knowledge-based Building Management System (BIM-IKBMS) for inspecting post-construction energy efficiency (GhaffarianHoseini, Zhang, et al., 2017).	Review	Post-Construction
The Benefits of, and Barriers to, Implementation of 5D BIM for Quantity Surveying in New Zealand (Stanley & Thurnell, 2014).	Interview	Construction

Developing a Building Information Modelling Educational Framework for the Tertiary Sector in New Zealand (Miller, Sharma, Donald, & Amor, 2013).	Framework	Education

3.8 Summary

This chapter presents the results of a literature review on the existing works and New Zealand context separately. In the existing work review parts, the development and evolution behaviors of the related technologies were identified. Such developing footprints provided a deep insight into the development of the proposed system. After investigating the evaluation method in BIM subject, this research emphasized the significance of adopting empirical methods. On the other hand, the BIM adoption in New Zealand was investigated among the existing surveys. It was suggested that BIM adoptions in the design and construction phases were much higher than in the operation phase. This highlighted the significance of conducting an exploratory design on topics in BIM operation. Last, this chapter will review the findings from other researchers and provide insights to the research design in the coming chapter. Finally, a discussion on the current BIM research in New Zealand reconfirmed the significance of this study.

Chapter 4 Research Methodology

4.1 Introduction

This chapter presents a review of the methodological arguments for the conduct of the entire research process. The first section aims to clarify the theoretical and conceptual frameworks for this study. It begins with a discussion of the barriers to conducting this research. Then, followed by an introduction of the "complexity" theory. Next, the rationale of adopting the proposed theory will be examined. After that, based on such a theory, a conceptual framework for the proposed research will be given. Such a conceptual framework will be further discussed on its functions.

The rest sections intend to describe the work flow of this study. From the review of literature presented in Chapter 3. It is evident that little research has been done on facilitating the information management in building O&M in New Zealand. Particularly, very little research has been conducted to examine the BIM-BMS integration in New Zealand. Having said that, the research outcomes from other countries can hardly be generalized directly into the New Zealand context. Hence, a knowledge gap exists in the current research subject area in New Zealand. For that reason, this study aims to address the issues in the current information management process that takes place in the New Zealand building O&M. Wherein, the purpose of this exploratory sequential design will be to develop and test a solution for improving the building sustainable performance in the O&M in New Zealand.

This research follows relativism. It believes: (1) multiple realities exist (2) Shaped by context (3) Truth evolves and changes (4) May use in similar contexts.

Prior to commencing this study, we conducted a literature review to capture the research problems. Upon these problems, we identified the barriers to solving them. Besides, the potential solutions were identified to remove the barriers as well and named as the global suggestions. Meanwhile, the specific terminologies used in this study were defined by documentation analysis. This method admit that the definitions are evolving based on time and it is also context-sensitive. Since then, the data collection began to conduct (See the research design in Figure 7). There are two phases of data collection:

The first phase is a qualitative exploration of the current limitations in New Zealand existing building management processes and the solution to them. During this phase, the global barriers were filtered into specific barriers by conducting a focus group interview the New Zealand industry experts. Likewise, the global suggestions were filtered into specific suggestions for removing the specific barriers in the New Zealand AEC/FM industry. Based on these specific suggestions, the solution for removing the specific barriers was designed by using axiom design. This method admit that the research objects evolve and change based on context and time.

The second phase is a quantitative test of the effectiveness of using the proposed system. In this phase, an electronic prototype was prepared by using agile development. This method represents a welcome to change. A system has been divided into parts, and each part is developed individually. Once one part changes, the other parts can easily adapt to it. After that, a pilot test on the prototype was made in the selected educational building in New Zealand. The operation was simulated by inputting the real monitoring weather data. Compared to the conventional system, the energy savings by adopting the proposed system were measured. The results were used for validating the effectiveness of the proposed solution.

Meanwhile, two research routes were designed: data collection and demonstration. On the one hand, the data collection route was developed to clarify the data collection order. On the other hand, the demonstration route will be used for generating the conclusions once all results obtained.

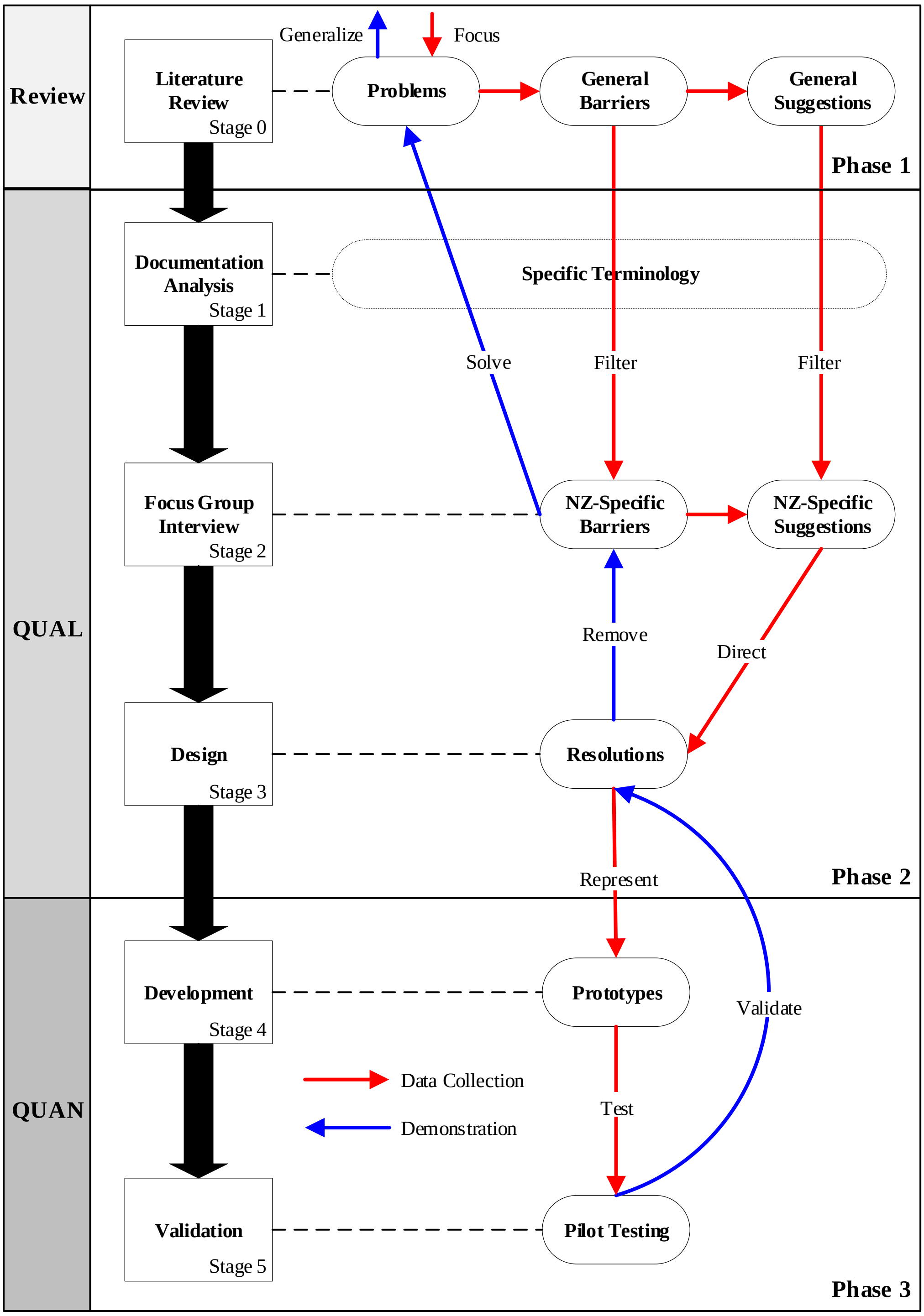


Figure 7 Research Design.

4.2 Theoretical and Conceptual Framework

4.2.1 Theoretical Framework

This research proposes to investigate the effectiveness of BIM-BMS integration in managing existing educational building facilities in New Zealand. For this purpose, this study developed and evaluated solutions for integrating the fragmented information.

Provided that, the technology is developing fast. Three barriers for developing solutions are brought by this phenomenon:

At the very beginning, the terminologies covered in this study are time and context sensitive. Some of the terms are defined globally, and it will be easily generalized into other countries (T.-W. Kang & Choi, 2015). Whereas, others will hardly be accustomed to a specific context. Thus, research conducted with out-of-date or non-context-specific terminologies will probably deviate the research outcomes from the research objectives.

Second, the technologies used in the whole solution continually evolve. A system must be flexible enough to the technology evolution. Because the modules wherein are interacted with each other. That's said, a new part can be difficult to adapt to the whole system. This significantly increases the complexity of the developing processes.

Third, this study proposed a cross-disciplinary solution to the research problem. On conditions that, transforming this "cross-disciplinary" solution into an "multi-disciplinary" solution becomes the pre-condition of the development process. This "multi-disciplinary" solution covers numbers of scales or levels. Only one single academic field should be involved in an individual basic unit. A single academic field has come to be used to refer to the knowledge branch which a typical individual researcher/engineer in the real world is capable of.

In regard to the above matters, the solution is complex. From the literature, there are a number of ways in which a solution can be identified as a complex system. Senge (1990) noted that "a system presents dynamic complexity when cause and effect are subtle, over time". As mentioned before, each part of our proposed system presents dynamic complexity in the evoving technologies. In the meanwhile, the various modules and their interactions aggravate the complexity degree. This has been approved by J. M. Sussman (1999), noticing that "a system is complex when it is composed of a group of related units (subsystems), for which the degree and nature of the relationships are imperfectly known". Likewise, "a system is complex when it is composed of many parts that interconnect in intricate ways" (J. Sussman, 2000). Hence, our proposed solution should be examed as a complex system.

For this purpose, the "complexity" theory is used as the lens to exam this topic throughout the entire research process. According to Don C. Mikulecky (2001), "complexity is the property of a real-world system that is manifest in the inability of any one formalism being adequate to capture all its properties". It gives a vision into the real-world systems paired with their scales. From a complexity theory viewpoint, this study should divide the system into numbers of parts and then exam those parts in a context formulated based on dynamics (Donald C. Mikulecky, 2007). Numbers of benefits from this are provided:

At the very beginning, this study converts the research problem from a cross-disciplinary to a multi-disciplinary problem. The proposed solution is reduced into parts. Towards the development of each single part, a single discipline knowledge is needed. This makes the parts be developed by different people or organizations. By using it, they should integrate them together. Whilst the relations between each part are already identified based on the complexity theory.

Then, once a module changes, the others should be flexible enough to it. All modules of the proposed system are independent to each other. Though these modules interact with each other. Information is transformed from one module to another. All modules should be established independently. Besides, the interface between each interacted module should be standardized (Schuh, Rudolf, & Breunig, 2016). Rather than totally replace the old system, a new system is developed in a standard way. Provided that, a new module should be developed following the interoperability rules. Such new module will replace the old one.

Having said that, the technology used in developing the whole system should base on a range of New Zealand specific or compatible terminologies. Such terminologies were identified in this study. However, this study is still limited in the adaptiveness in a situation when the terminology evolves.

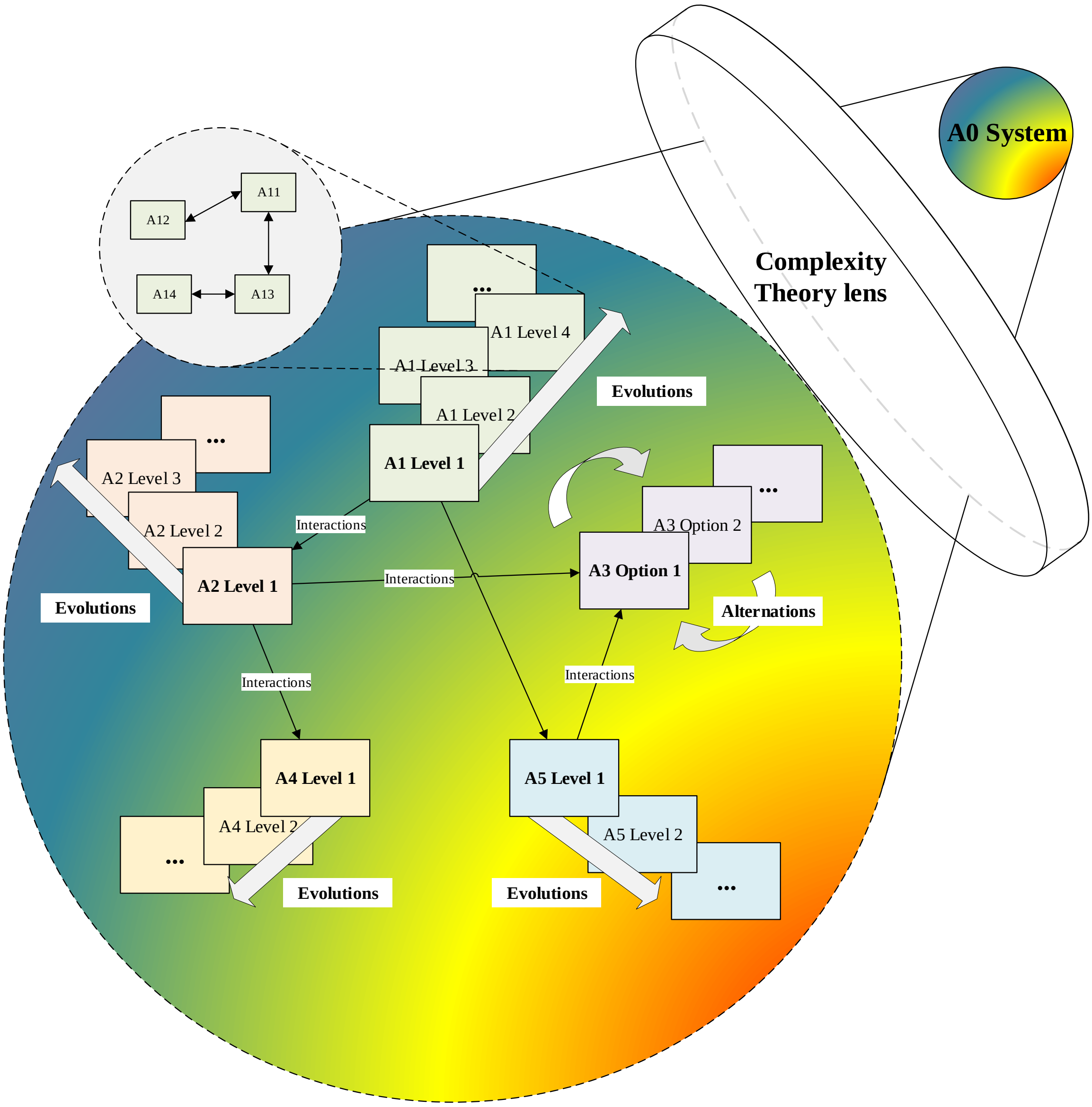


Figure 8 Visions of This Study through "Complexity" Theory Lens.

4.2.2 Conceptual Framework

A conceptual framework of the proposed solution is developed (See Figure 8). This study reduces the system into basic modules. And then exams them in a context formulated based on dynamics. The proposed solution is developed based on an nD BIM-IKBMS conceptual framework. The nD BIM-IKBMS was first established by GhaffarianHoseini, Tookey, and GhaffarianHoseini (2014). Such a framework provides simulation-based supervisory control while automatically detecting and diagnosing operational faults. The significance of the nD BIM-IKBMS has been validated by GhaffarianHoseini, Zhang, et al. (2017). It is found to be that the proposed system can improve the effectiveness of building O&M information management. As illustrated in Figure 9, this study identifies the inputs, outputs, tools, and constraints of the nD BIM-IKBMS model. The plotting standards of this conceptual model will be illustrated in Section 4.5.

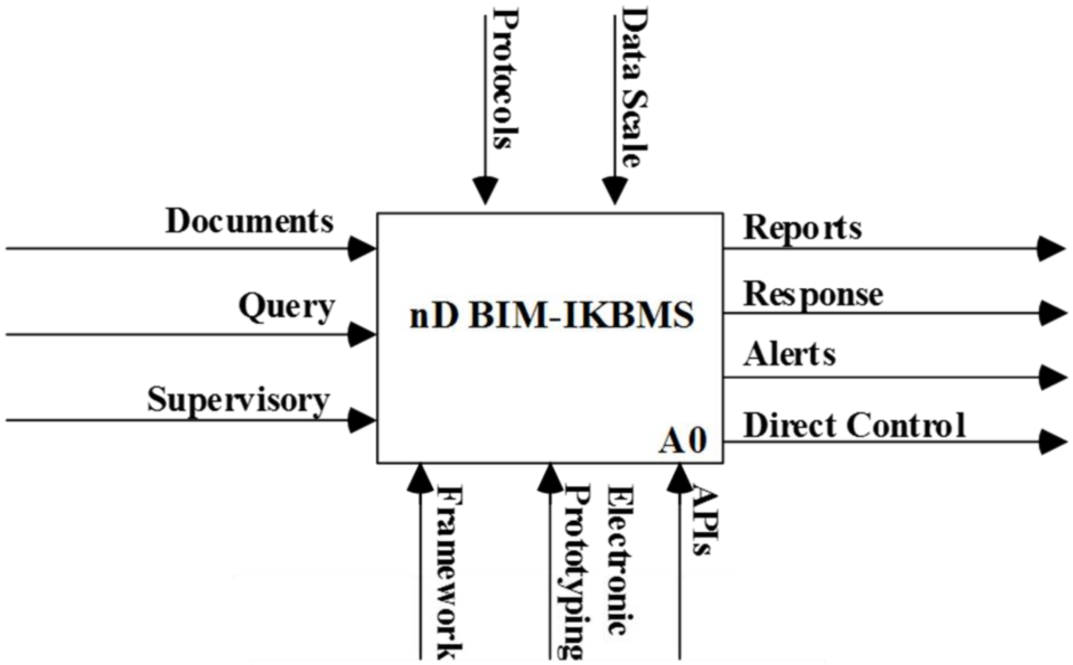


Figure 9 Conceptual Framework: The ND BIM-IKBMS Model.

There are three types of inputs for the proposed system, they are:

(1) The proposed system stores construction handover documents, as-built BIM models, and other documents required for operating and maintaining a building. It works as a database for all the building management data.

(2) The proposed system conducts reasoning in response to the query input. When the FM people get a situation, the end user can retrieve the simillar cases for maintenance solutions. The situation can be an operational failure, or even a duct corroded.

(3) The end user oversees the proposed system on managing the direct control. Commands for direct control can be sent by the end user. Also, strategical scheme for the FM can be made by adjusting the event listener.

There are four types of outputs for the proposed system, they are:

(1) The proposed system can generate a building performance simulation report to the end user. The results from such reports can be used to predict the energy consumption under specified conditions. This helps the decision-making process for O&M.

(2) The proposed system answers to the queries with solutions obtained from its knowledge base. These solutions will guide the end user gradually to sort the problem out. Then, the end user can update the knowledge base through rating the retrieval results.

(3) The proposed system will alert the end user when asset warranty is expired, illegal operation is taken, or any other faults are detected. In which, the typical faults can be matched with their location in principle. And these faults can be directly sent to the retrieving system once occur. Also, the typical operation failures will be updated into the proposed system by the end user for future troubleshooting.

(4) The proposed system sends the commands that directly control the devices. These commands can be sent either directly from the end-user input or by event listeners who keeps on programming the sensors.

There are three types of resources for the proposed system, they are:

(1) The proposed system implements an existing framework for developing the software or deploying the hardware. As discussed above, a SCADA framework can be adopted for supervisory control and data acquisition. In which, the SCADA level of the proposed framework should be determined. With the rapid development of SCADA technology, the fourth level of SCADA – the IoT is more and more commonly used around world.

(2) The proposed system can be established by using numbers of existing APIs. For a higher visualization of the building information, Autodesk Forge APIs are widely adopted around the world. It packages an expending collection of web service components that can be used with Autodesk cloud-based products. It saves time from programming repeatedly for the existing UI functions. Instead of depending on APIs whose Intelligent Property (IP) owned by other organizations, open source libraries such as OpenGL, WebGL are preferred for interacting with a graphic processing unit.

(3) The proposed system can be tested in electronic prototyping. There are numbers of open-source electronic prototyping platforms such as Arduino, Raspberry Pi, and so on. The proposed system can be easily programmed and rapidly prototyped by using these platforms.

There are two types of constraints for the proposed system, they are:

(1) The hardware deployed in the proposed system should be configured with the right serial communication protocol. Serial communication happens when sending data one bit at a time sequentially over a communication channel or computer bus. There are various protocols such as Modbus series. They are usually used to connect a supervisory computer with a Remote Terminal Unit

(RTU) in a SCADA system. On condition that, the protocols are developing and updating as well.

(2) The effectiveness of the proposed system is limited to the data scale it faces. Take operation fault monitoring as an example, it might be dropped down when it keeps on receiving thousands of alerts every second.

In summary, the conceptual framework established here is a functional overview. To put it into another way, it is a general function design with inputs, outputs, tools, and constraints. However, it still depends on cross-discipline technology. Based on the complexity theory, the proposed conceptual framework should be deepened into more basic units.

4.3 Stage 1: Documentation Analysis

During the documentation analysis stage, inductive research was carried on for forming the research terminology (Jebb, Parrigon, & Woo, 2017; Woo, O'Boyle, & Spector, 2017). Particularly, it identified the research problem, barriers, paired with the potential solutions. Prior to commencing this research, abstract-based filtering was conducted to select the relative publications. In order to satisfy the objectives of this research, Word-Frequency-Based Topological Data Analysis (WTDA) approach was held (See Figure 10).

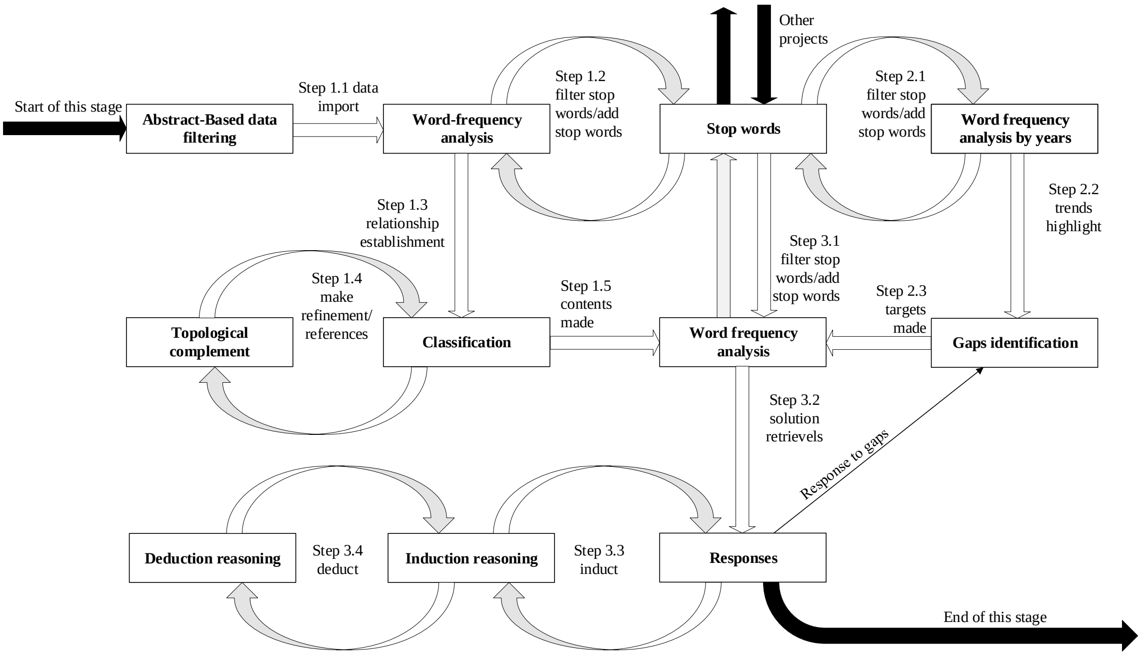


Figure 10 Research Process in the Documentation Analysis Stage.

WTDA is an inductive research approach, which specializes in a subject that is in its fast developing. This means neither over-conceptual nor fully-developed, such as BIM, Smart Grids, and so on. Word-Frequency-Based (WFB) analysis, including relational analysis (Karin J. Gerritsen-van Leeuwenkampa, 2017), cluster analysis (Gabor, 2009), and thematic analysis(A.Waters & AngusBuchanan, 2017), are used in corresponding phases. In addition, topological data analysis is used for the complement of the WFB classification. Among the pre-existing methods, the grounded theory was frequently used in such fields (Zulfiquar N. Ansari, 2017). However, this method lacks demonstration from the documentation perspective (Rodrigo Ramalho, 2015). Also, WFB analysis exists potential threat that the results are overlooked (P. R. Woubshet Nema Behutiye, Markku Oivo, Ayse Tosun, 2017). Moreover, topological data analysis for industry data is overloaded when massive data is required (Gabor, 2009). The WTDA has a number of useful features, including:

(1) A WFB analysis used in this method has been proven effective in content analysis and found to reduce the influence of research bias (Edgar E. Hassler, 2018).

(2) Topological complement is used to refine the classifications so that the misinterpretation of results can be minimized (P. R. Woubshet Nema Behutiye, Markku Oivo, Ayse Tosun. , 2017).

In order to identify the most responsive traits, the procedures were followed: first, journal articles in Elsevier, Springer, and Taylor & Francis were retrieved and filtered. Currently, there are more and more journals in almost all areas. Some provide restricted access while the others offer open access. Considering both of the citing frequency and accessibility, the most suitable journal publishers were determined as above. Then, WFB analysis was made to construct the classification tree associated with relational analysis, cluster analysis, and thematic analysis. Next, a topological complement was made to avoid misinterpretation from automatic keyword extraction process. After that, year-based keyword extraction was made based on frequency. Thereafter, the terminology for BIM was formed. Last, based on the terminology established, the research problem, barriers, and potential solution were identified.

Data for this study were retrospectively collected from academic publications published from the most popular publishers. Refer to Vincent Larivière (2015), 55% scientific publications were published by Reed-Elsevier, Springer, Wiley-Blackwell, Taylor & Francis, and Sage. Wiley-Black. Regarding the novelty, accessibility, and time-consuming, we decided to collect scientific journals, conference papers instead of books and other formats of publication.

Prior to the retrievals, we have a quick check of those five publishers. Amongst them, Wiley-Black only published books in BIM field. Those books were from the perspective of skills training. Thus, we excluded Wiley-Black from our data collection. Meanwhile, when retrieving BIM related publications in SAGE journals, only eight journals were found. The sample was too small to examine; hence it was excluded from this research.

Therefore, three most popular academic search engines were retrieved in 18/02/2018: Elsevier, Springer, and Taylor & Francis. In the first-round selection, we searched "BIM" or "Building Information Modelling" in all contents, and massive results were hit, more than 380, 000 articles in total. To shortlist the most relative data, I filtered the results in the second round: to maximize the extent of relating to BIM, I searched articles with "BIM" or "Building Information Modelling" only in their titles. To maximize the quality of data, the hit frequency of journals are listed, and we filtered the data with most relevant journals, which had at least three hits in this research. At this stage, 497, 30, and 28 results were found in Elsevier, Springer, and Taylor & Francis separately. For the purpose of analysing the trend of BIM in the literature, we made the results into 9 groups based on the published year (1975-2018). (See Table 6, Table 7, and Table 8)

Table 6 Data Selection and Filter Criteria in Elsevier.

Round	**Years**	**Criteria**	**Results**
1	All years	TITLE, ABSTRACT, KEYWORDS (BIM) or TITLE, ABSTRACT, KEYWORDS (Building Information Model) [Type: Journal Articles, All Sources (Computer Science, Earth and Planetary Sciences, Energy, Engineering, Environmental Science, Materials Science, Social Sciences)].	3,761
2	All years	TITLE(BIM) or TITLE (Building Information Model) [Type: Journal Articles, All Sources (Computer Science, Earth and Planetary Sciences, Energy, Engineering, Environmental Science, Materials Science, Social Sciences)]. LIMIT-TO ("Automation in Construction, Procedia Engineering, Advanced Engineering Informatics, Energy and Buildings, Energy Procedia, International Journal of Project Management, Procedia - Social and Behavioral Sciences, Journal of Cleaner Production, Sustainable Cities and Society, Safety Science, Building and Environment, Journal of Building Engineering, Procedia Environmental Sciences, Renewable and Sustainable Energy Reviews, Computers, Environment and Urban Systems, Computers in Industry, Advances in Engineering Software, Resources, Conservation and	497

		Recycling, Serials Review, Tsinghua Science & Technology") AND	
3	- 1979	Pub-date < 1979 AND	0
	1980 1984	Pub-date > 1980 and pub-date < 1984 AND	0
	1985 1994	Pub-date > 1985 and pub-date < 1994 AND	0
	1995 1999	Pub-date > 1995 and pub-date < 1999 AND	2
	2000 2004	Pub-date > 2000 and pub-date < 2004 AND	0
	2005 2009	Pub-date > 2005 and pub-date < 2009 AND	11
	2010 2014	Pub-date > 2010 and pub-date < 2014 AND	130
	2010 2014	Pub-date > 2010 and pub-date < 2014 AND	130
	2015 2018	Pub-date > 2015 and pub-date < 2018 AND	294
		TITLE(BIM) or TITLE (Building Information Model)	

Table 7 Data Selection and Filter Criteria in Springer.

Round	**Years**	**Criteria**	**Results**
1	All years	ALL CONTENTS (BIM) or ALL CONTENTS (Building Information Model) [Type: Journal Articles, All Sources (Computer Science, Earth Sciences, Engineering)].	376, 723
2	All years	TITLE(BIM) or TITLE (Building Information Model) [Type: Journal Articles, All Sources (Computer Science, Earth Sciences, Engineering)].	40

		LIMITED TO (“Visualization in Engineering, KSCE Journal of Civil Engineering”, “Archives of Computational Methods in Engineering”)	30
3	- 1979	Pub-date < 1979 AND	0
	1980 1984	Pub-date > 1980 and pub-date < 1984 AND	0
	1985 1994	Pub-date > 1985 and pub-date < 1994 AND	0
	1995 1999	Pub-date > 1995 and pub-date < 1999 AND	0
	2000 2004	Pub-date > 2000 and pub-date < 2004 AND	0
	2005 2009	Pub-date > 2005 and pub-date < 2009 AND	0
	2010 2014	Pub-date > 2010 and pub-date < 2014 AND	3
	2015 2018	Pub-date > 2015 and pub-date < 2018 AND	27
		TITLE(BIM) or TITLE (Building Information Model)	

Table 8 Data Selection and Filter Criteria in Taylor & Francis.

Round	**Years**	**Criteria**	**Results**
1	All years	ALL CONTENTS (BIM) or ALL CONTENTS (Building Information Model)	629
		[Type: Journal Articles, All Sources (Built Environment, Engineering & Technology, Economics, Finance, Business & Industry, Education, Geography, Computer Science, Environment and Sustainability, Urban Studies, Earth Sciences, Arts)].	
2	All years	TITLE(BIM) or TITLE (Building Information Model)	54
		[Type: Journal Articles, All Sources (Built Environment, Engineering & Technology, Economics, Finance, Business & Industry, Education, Geography, Computer Science, Environment and Sustainability, Urban Studies, Earth Sciences, Arts)].	
		LIMITED TO (“Construction Management and Economics, International Journal of Construction Education and Research”, “International Journal of Construction Management”, “Journal of Building	28

		Performance Simulation", "Journal of Civil Engineering and Management")	
3	- 1979	Pub-date < 1979 AND	0
	1980 1984	Pub-date > 1980 and pub-date < 1984 AND	0
	1985 1994	Pub-date > 1985 and pub-date < 1994 AND	0
	1995 1999	Pub-date > 1995 and pub-date < 1999 AND	1
	2000 2004	Pub-date > 2000 and pub-date < 2004 AND	0
	2005 2009	Pub-date > 2005 and pub-date < 2009 AND	2
	2010 2014	Pub-date > 2010 and pub-date < 2014 AND	13
	2015 2018	Pub-date > 2015 and pub-date < 2018 AND	12
		TITLE(BIM) or TITLE (Building Information Model)	

4.4 Stage 2: Focus Group Interview

With the results from documentation analysis, a focus group interview stage follows. This study intends to investigate the effectiveness of BIM-BMS integration in managing existing educational building facilities in New Zealand. Many researchers have utilized literature analysis to identify the pros and cons of a specific technique in the AEC/FM industry (Bradley et al., 2016; Zou, Kiviniemi, & Jones, 2017b). However, a major problem with such a method is that the statistics referred from the literature might not be justified enough.

As mentioned in our literature review section, the most popular used BIM adoption surveys in New Zealand were conducted by Eboss. As an online library of product catalogs from 219 of New Zealand's leading architectural product suppliers, Eboss collaborated with BIM Acceleration Committee and sponsored the research initiative.

The increase in BIM adoption in New Zealand will improve the benefits of Eboss. That is to say, the potential of BIM-BMS integration could also be either amplified or ignored due to the conflicts of interest. Similarly, conflicts of interest also exist in the interview method for this purpose. Some of the interviewees from the BIM consultancy might even intend to accelerate BIM marketing by giving a positive answer.

This research adopts a focus group interview method. Refer to Krueger (1994), a focus group interview is “a carefully planned discussion designed to obtain perceptions on a defined area of interest in a permissive, non-threatening environment”. To put it in another way, Morgan (1998) describe a focus group as “fundamentally a way of listening to people and learning from them”. Compare to other survey methods of collecting data such as interviews, questionnaires, participant observation, and so on, focus group interviews offer several advantages.

Comparing to an individual interview, such method provides a more natural environment where participants “are influencing and influenced by others – just as they are in real life” (Krueger, 1994). In a focus group interview, coupled with the complex negotiation of the on-going interaction processes among participants, multiple views and attitudes are gained. By contrast, the results from individual interviews largely depend on individual beliefs and attitudes. Besides, biases exist in individual interviews that such beliefs and attitudes are more likely controlled by the interviewer than they are in focus group interviews.

Meanwhile, focus groups are commonly used to occupy a middle ground between participant observation and in-depth interviewing (Morgan, 1998). Rather than interview, this study adopted the focus group method with an emphasis on observation. Refer to Litosseliti (2003), such emphasis will result in “exploratory, qualitative, naturalistic or interpretative groups”.

Prior to commencing the focus groups, the sample size including the group size and the number of groups should be determined. Depending on the right number of participants for a focus group, requires balancing the generation of enough discussion and high participant engagement. Refer to Morgan (1998), the typical group size is six to ten with 60-120 minutes duration. Such group size usually accomplishes the requirements.

Despite, there are numbers of exceptions where a smaller group is more suitable to be adopted. The more participants recruited, the shorter time per participant per question. To attain a more in-depth understanding of what participants have said, smaller groups are preferred. Refer to what Morgan (1998) said, the requirements for recruiting smaller groups are (1) “when participants are emotionally caught up in the topic”. (2) “when the topic is controversial”; (3) “when the topic is complex”. (4) “when the participants are experts or know a lot about the topic”. (5) “when participants have a high level of involvement with the topic”. Provided that, the participation of such focus group interview is voluntary while all the participants are strangers to the research before conducting this study. They are holding the same interest on this topic as the researcher. Thus, they are more likely to catch up on this topic emotionally during the interview. Also, the FM has been identified as the bottleneck of BIM adoption all over the world. Some researchers promoted BIM in FM while others hold resistance to this new technology. To put it into another way, this topic is controversial.

This study is an explore design, and the solution was missing at this stage. By collecting detailed materials of the participants’ past experience and their vision of development of some advanced technology are essential. On conditions that, our proposed system has been identified as a complex system. For a smaller group, there is need to recruit participants with more expertise. Such experts are expected to be the key player of New Zealand FM industry. This facilitates the delivery of a higher level of participant involvement during the interview. Therefore, to get a deeper understanding of the research topic from the participants while remaining the comfort of participation during the interview, this study decides on recruiting five expert participants in each group for 120 minutes.

As for the number of groups, it is time- and cost- consuming for assembling more than one groups of expertise participants. Scheduling a 120-minute interview for all the expert participants in a group is never easy. For such reasons mentioned above, Morgan (1998) stated that “using just one group is risky, not wrong”. Besides, this research intends to provide a solution for the current New Zealand FM. Such solution is complex and cross-discipline, which FM engineers with less experience might not be able to get a whole picture on the knowledge that is needed. That said, the quality of the participants for this topic is more important than the number of groups organized. To put it into another way, a larger number of groups which deliver lopsided views might ruin this study (Lazar, Feng, & Hochheiser, 2017). Towards achieving a time-, cost-, quality- efficient focus group interview, this study determines to organize only one group among expert participants with at least 25-year experience in New Zealand FM industry.

For our purpose, the expert participants were recruited from different companies in BIM and BMS related field in New Zealand. Experts who have at least 25-year experience in New Zealand FM industry from a variety of backgrounds. (See Table 9) Such background includes but is not limited to consultancy, FM/AM company, FM software providers. To avoid of unjustified results, one participant can raise a question at any time to the others’ responses. Consequently, they might be unanimous in one view, or disputes still exist on that question. The results will be analyzed to identify the inconsistency between the literature and realities.

Table 9 Participant Information.

Experts	Job title	Years of experience
1	Director of an assets management company	38
2	General manager of an assets management company	31
3	Director of a facilities management company	26
4	Associate director of a facilities operations company	25
5	Director of a BMS provider	30

Despite this, the crucial limitation for the focus group designed is that the content of discussion cannot be separated from either the unique characteristics of the participants or their group dynamics. Facing this issue, a "triangulation" was designed. Refer to Adams et al. (2015), Triangulation is "a general approach whereby the convergence, complementarity, and dissonance of results on related research questions, obtained from different methodological approaches, sources, theoretical perspective, or researchers are explored". When a single focus group made, triangulation can help to determine whether the content of that discussion is consistent with information from other sources. In this study, a comparison between the results from the literature and focus group interview was conducted. The common results were verified mutually while the inconsistency of the data will be further examined. This includes either checking the accuracy of the data collected or demonstrating the gaps between literature and the industry.

The issue of research ethics should also be addressed. Litosseliti (2003) suggested that research ethics is "about the moral values and principles which guide and underpin the research process". First, prior to recruiting participants, how much to tell them about the research have to be determined. Towards this end, an ethics application has been submitted to the AUT Ethics Committee (AUTEC). The whole process has been designed in detail in the application documents. Provided that, the participant recruitment will not be started until the application approved by AUTEC. Wherein, a brief introduction of this study was sent to the potential participants to let them know what was going to happen. The participants have the rights on deciding on whether to participate. Also, they have the rights to retract their inputs at any time during this study (See the ethics approval letter in Appendix A).

Secondly, a particular issue to consider in focus group research is confidentiality (Morgan, 1998). It is difficult to assure participants of this, when they say is shared with others in the group and with the moderator. Since, before conducting this interview, a consent form will send to sign by the participants noticed that the discussion, as well as their personal information, might be disclosed among the discussion itself. To reduce the influence of this, in publications and thesis writing, their names paired with their affiliation information will be anonymous.

Third, the research process might usually involve ethical questions that involve around issues of power. This study has considered the power relations between the moderator and the participants, between the researcher and the participants, and between each focus group participant. As responses to these power issues, the researcher of this study, who moderated this focus group interview, is much younger than the participants. He is a PhD candidate at AUT University who arrived in New Zealand in 2016. Before this, he had never been to New Zealand. The participants were strangers to the researcher before conducting this study. Hence, there are no power relations between the participants and the researcher/moderator. Meanwhile, all the participants were recruited from different companies. Thus, the possibility of power relations has been minimized.

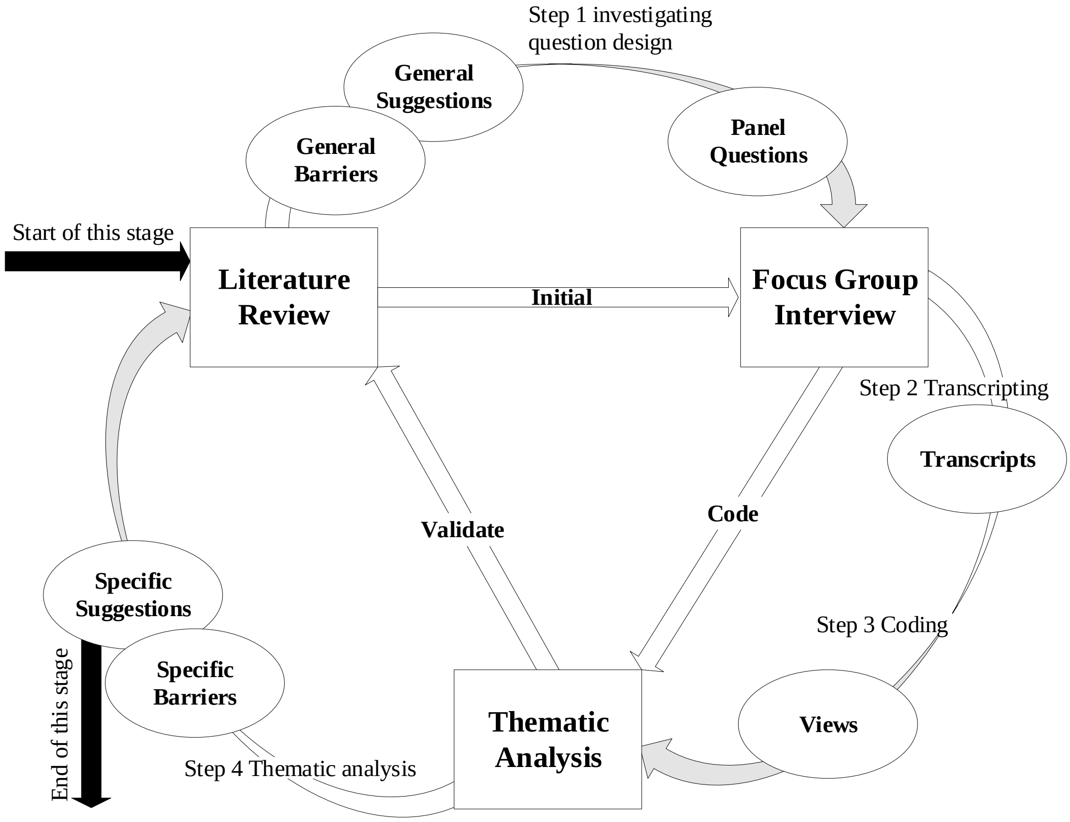


Figure 11 Research Process in the Focus Group Interview Stage.

The procedures of this research were illustrated in Figure 11. Prior to commencing this research, a literature review was conducted to identify the investigating questions. The focus group interview questions were then decided as followings: (1) What is the relationship between BIM and BMS? Is BMS a part of BIM? (2) What do you think about the BIM adoption in New Zealand? Is it fully used? (3) Is the BIM-BMS integration significant in supporting facility management in New Zealand? (4) What are the current limitations for BMS without BIM? (5) Why current BIM-BMS cannot meet the expectation? In the literature, the answers were collected for each question.

After ethical clearance was sought from AUTEC, five participants were recruited: one participant from facilities maintenance; one participant from facilities operations; one participant from a BMS provider; two participants from asset management. During the interview, the free discussion was made, and the responses were recorded.

Once the transcripts were created and checked, the interview data can be analyzed thematically. Five themes were identified: the relationship between BIM and BMS; the BIM adoption in New Zealand; The significance of the BIM-BMS integration in supporting facility management in New Zealand; The current limitations for BMS without BIM; The limitations of current BIM-BMS. After obtaining the responses to the questions, a comparison was carried out between the responses from the participants and the literature. Based on the results of this stage, a framework will be designed for the proposed system in the next section.

4.5 Stage 3: Axiom Design

Based on the complexity theory, the proposed solution should be modulized into basic units which only contains single discipline knowledge. While, these units should be independent in its forms. To satisfy both of these two requirements, an axiomatic design approach was adopted to develop the nD BIM-IKBMS conceptual framework. Refer to Suh (1990), "Axiomatic design is a system design methodology using matrix methods to systematically analyze the transformation of customer needs into functional requirements, design parameters, and process variables". Such an approach provides a scientific base for system research and development that supports the creativity of designers. Additionally, it reduces the random searching process, shortens the iterative process of trial and error, clarifies the assessment principles of design, and endows the computer with the capacity to create (Schuh et al., 2016). This proposed system was designed based on independence axiom, information axiom and their inferences for axiomatic design. By following the independence axiom, the proposed system can be highly flexible for the evolution of its parts (Avin, Borokhovich, Lotker, & Peleg, 2017). Besides, with the information axiom, the best scheme can be selected. Provided that, this study should meet the requirements of the independence axiom, however, the information axiom will be left as a principle for future study to refine this system (Avin et al., 2017).

Integrated Computer-Aided Manufacturing DEFinition for Function Modeling (IDEF) is a function modeling methodology that consists of a hierarchical series of diagrams, text, and glossary cross-referenced to each other (Waissi, Demir, Humble, & Lev, 2015). By using IDEF0, this study can conduct an axiomatic design for reducing the complexity of the proposed system. A typical IDEF0 box used in this study has been illustrated in Figure 12. As we can see from the illustrations, Structured Analysis and Design Technique (SADT) language is used in IDEF0 to describe the proposed system. Such diagrams are used to define the proposed functions while arrows are used to identify the relationship between these diagrams (Leonard, 1999).

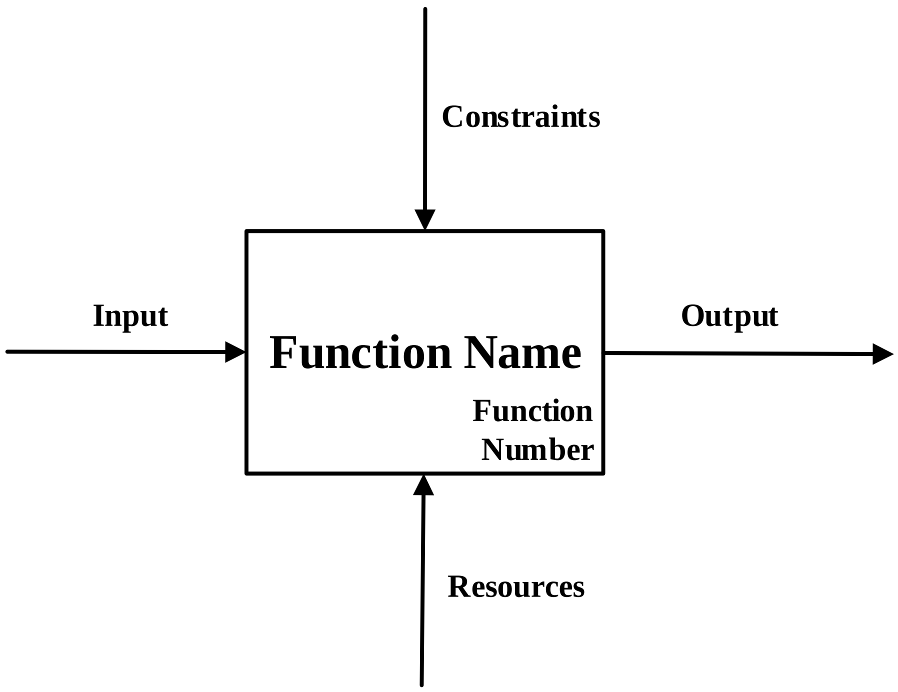


Figure 12 IDEF0 Box Used in This Research (adapted from Leonard (1999)).

As discussed above, this study follows the complexity theory and designed the proposed system by using axiomatic design approach with IDEF0 tools (Avin et al., 2017). The research process for this stage has been illustrated in Figure 13. Prior to commencing this stage, a focus group interview was done for filtering the specific barriers paired with their specific suggestions. Based on this information, the Customer Attributes (CAs) were determined. After that, the mapping between CAs and Function Requirements (FRs) was carried on. The functions for the proposed system have been determined. Next, this study aligned Design Parameters (DPs) to these FRs. The functional models were built at this step. Then, the relationships between FRs and Process Variables (PVs) were linked. Last, the design scheme should be verified by Independence Axiom while evaluated by using information axiom. To make this research sustainable, a refined design in the future is welcome. Once the new scheme shows the less information content while maintaining the independence features, the old scheme can be replaced by the new one. The design in this study should satisfy the Independence Axiom to maintain the flexibility for each part of the proposed system. Despite this, the information content of the proposed system should be further optimized based on the information axiom in the future.

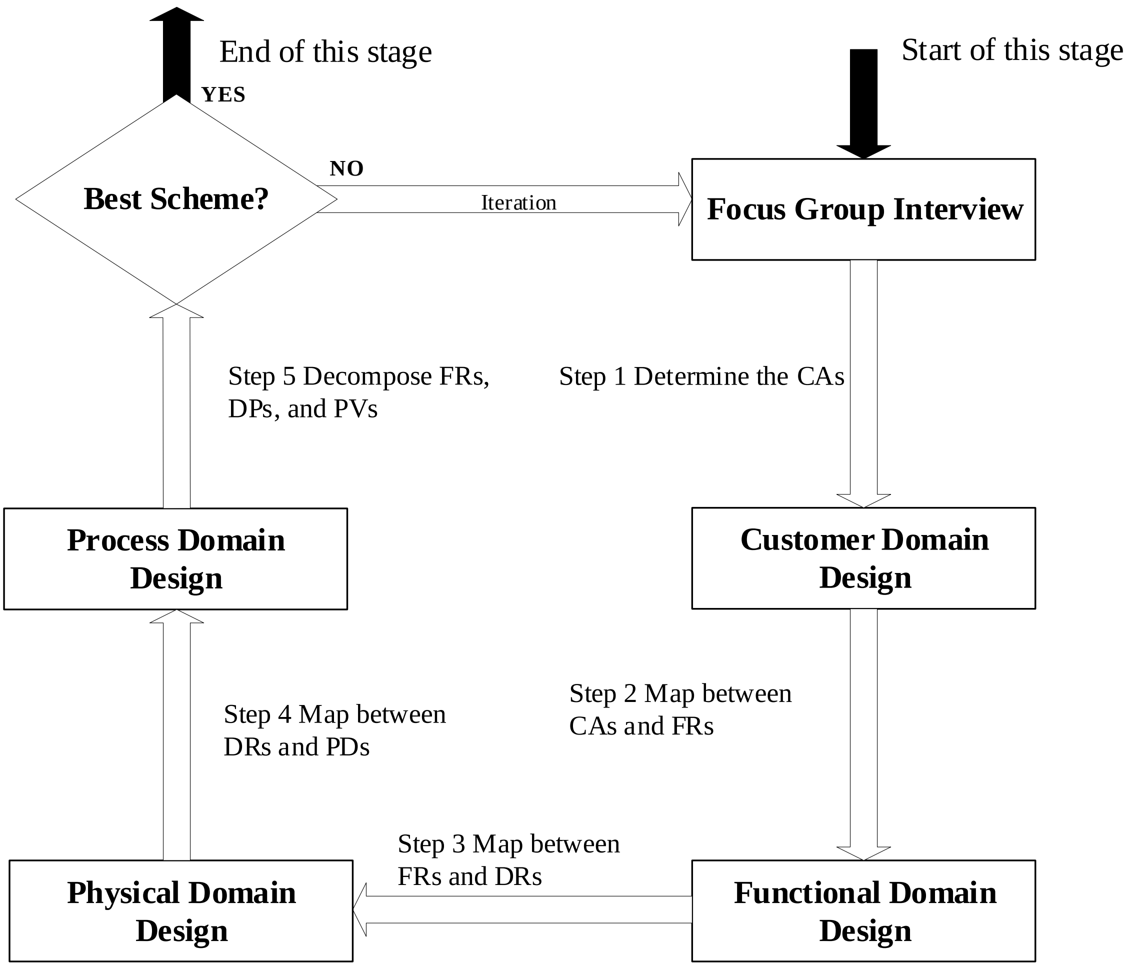


Figure 13 Research Process in the Design Stage.

4.6 Stage 4: Agile Development

This study applied the complexity theory to developing a solution for solving the issues in building facility information management. It is expected that each part in the proposed system keeps on evolving over the time. Towards this end, the proposed system was divided into numbers of basic parts which is independent of each other. Once one part evolves, the others can highly adapt to it. To put it in another way, when changes are needed, the developers will only need to replace the related part rather than update the whole system.

However, traditional software development methods such as "waterfall", "Spiral", "Iterative" can hardly facilitate this need (Watkins, 2009; Younas, Jawawi, Ghani, Fries, & Kazmi, 2018). In the beginning, they all adopt a plan-develop-test pathway which is not "sensitive" enough to the changes. When the customer requirements change, the developers might need to adapt this change to the whole system. Secondly, the traditional developers most commonly involve the customers only at the beginning. Rare communication between the customers and the developers is made during the development stage. Thirdly, by using those old-school methods, the developer can hardly engage in the post-development stage. The products can barely be maintained after releases. (Patanakul & Rufo-McCarron, 2018) Facing these issues, an agile approach was adopted by this research.

Agile refers to any process that aligns with the concepts of the Agile Manifesto. Refer to the Agile Manifesto (Beck et al., 2001), “agile processes harness change for the customer's competitive advantage”, “promote sustainable development”, and engage “continuous attention to technical excellence and good design”. There are numbers of agile methods for developing a software solution, such as Adaptive software development, Agile modelling, Agile unified process, Disciplined agile delivery, Dynamic systems development method, Extreme programming, Feature-driven development, Lean software development, Kanban, Rapid application development (RAD), Scrum, Scrumban, and so on (Campanelli & Parreiras, 2015).

After a comparison among them, A RAD method is selected by this study. Compared to other agile methods, RAD’s method puts more emphasis on development than planning tasks (Chandra et al., 2018; Ma & Liu, 2018). Especially, such an approach follows an incremental model, where each component is developed in parallel. To develop a framework that keeps on evolving itself, the RAD method shows high efficient in developing systems that are component based and scalable (Qureshi & Hussain, 2008). Wherein, a prototype approach is adopted in the user design phase to deliver more complete user requirements. With shorter planning cycles, it’s easy to accommodate and accept changes at any time during the project or even after finished. Meanwhile, the customers are highly engaged in each small cycle.

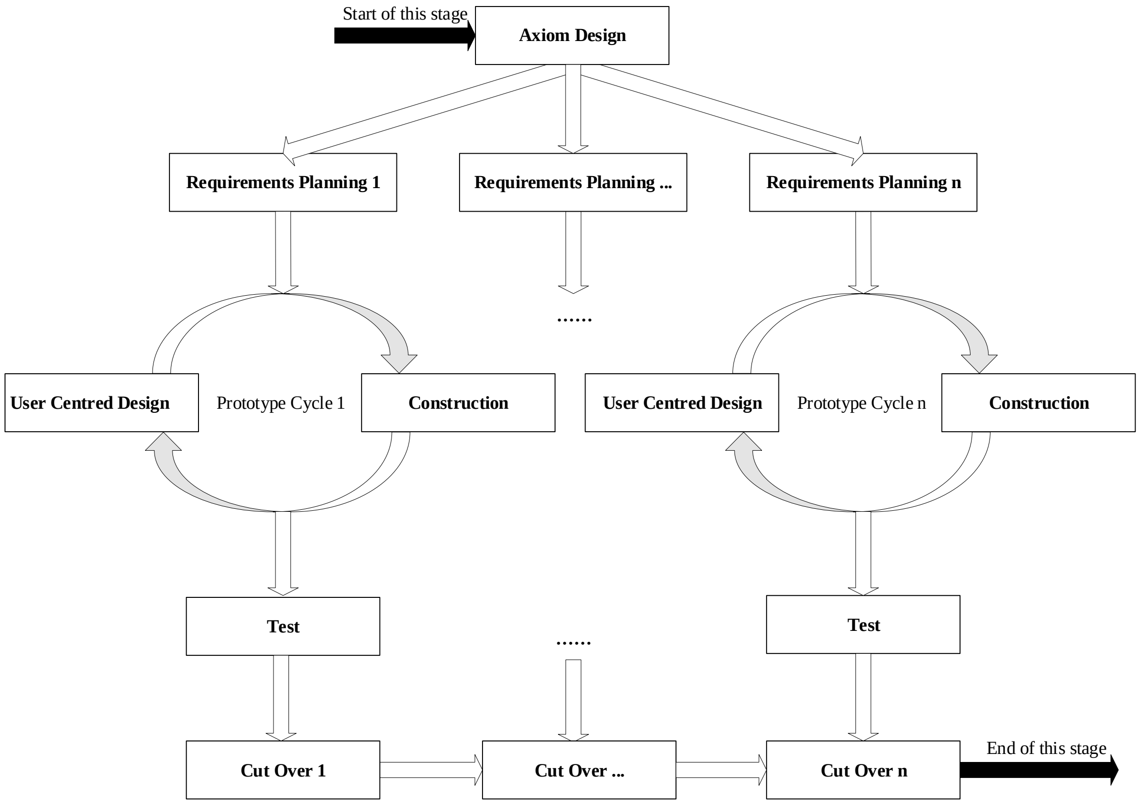


Figure 14 Research Process in the Development Stage.

By adopting the RAD method, the process during this stage has been illustrated in Figure 14. As the solution has been broken down into several parts in the axiom design stage, each part can be developed and tested separately. This allows the developers to focus on high-quality development, testing, and collaboration (Campanelli & Parreiras, 2015). Carrying on testing during each iteration, the bugs can get identified and solved more quickly. With consistent, successive iterations, the solution can be delivered faster while remains developing sustainability. Besides, customers will be more frequently engaged in a focus group interview as they are more concerned about the capacity of product. In this study, the potential customers, whom the proposed solution might benefit, are mainly the FM teams while this benefit can be delivered more effectively once the building development teams use the proposed solution as well. By satisfying their requirements, numbers of end-user engagement meetings were held during the whole projects. Rather than only satisfy the main end user – FM teams, the researcher of this study has made frequent communication and face-to-face interactions with all the potential end users during the user centred design and construction steps. Such idea facilitates the strategy of designing for maintenance put forward by BRANZ (Pringle, 2015).

4.7 Stage 5: Pilot Testing

To validate the effectiveness of the solution established in the qualitative phase, the prototype developed in the previous stage was tested. A pilot deployment before a full rollout is essential. Refer to Hulley, Cummings, Browner, Grady, and Newman (2013), a pilot test is "a small scale preliminary study conducted in order to evaluate the feasibility, time, cost, adverse events, and improve upon the study design before the performance of a full-scale research project". Rather than apply to the whole building, we prefer to select a room wherein so that once it is not effective as previously was, we still can revise it until it works as expected.

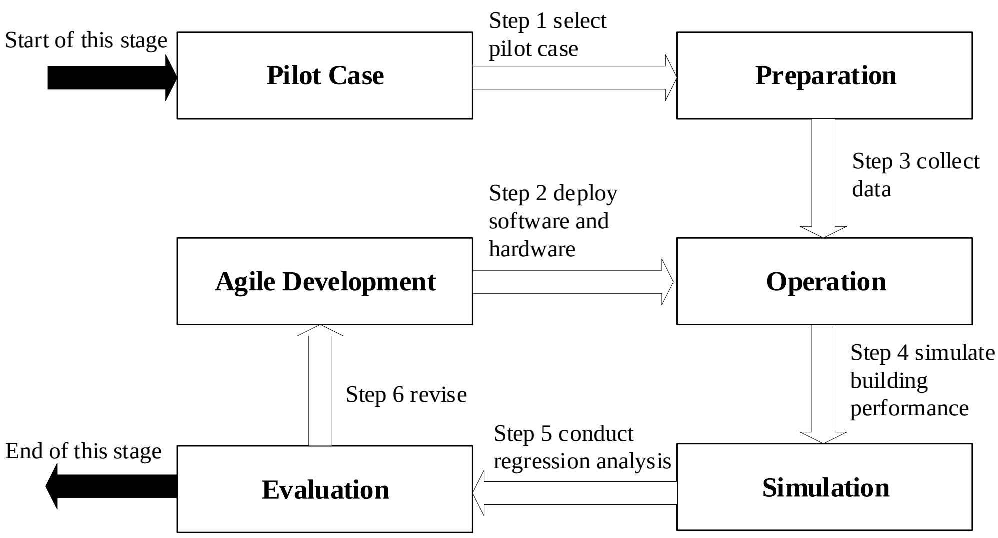


Figure 15 Research Process in the Pilot Testing Stage.

The process for this stage is shown in Figure 15. As presented, a pilot case should be selected before commencing this stage (Donald, 2018; Harrison, 2019). In view of the research scope for this study, three rules were met for the pilot case selected: a building in New Zealand, an educational building, and the most accessible building by the researcher. After that, the prototype was deployed under the pilot case conditions where the data was collected. Next, a simulation should be run in MATLAB analysing the data collected. Once obtained the results of this simulation, a regression analysis was carried on to minimize the uncertainties in the data collection. Eventually, the results were used for evaluating the pilot case while the solution was tested.

To test the attributes from BIM and BMS separately, we designed three operate scenarios for managing HVAC in the pilot case: (1) operation without BIM or BMS, (2) operation with BMS, (3) operation with BIM-BMS integrated. In the traditional operation where neither BIM nor BMS exists, the sensor keeps on monitoring the temperature from the terminal. This is much different from the mean indoor temperature. To reduce the tolerance between the monitoring data and the mean indoor temperature, BMS was adopted.

As mentioned in the literature, the BMS is short in data analysis where BIM can simulate the building performance. Thus, with a sensor deployed and maintained without BIM, the temperature monitored is assumed to be less efficient as the one coupled with a BIM-assisted BPS. It was noted that most of the BMS control algorithms adopt the well mix model. That is because they have to assume the room air is homogeneous if the monitored data cannot be analyzed further. To resolve this issue, BIM was integrated for simulating the performance and finding the most accurate mean indoor temperature value.

Several methodological assumptions were made in the simulation step. Refer to Yang (1999), a majority of the existing models used for such field were oversimplified, where the room air was always assumed as perfect mixed. In fact, however, the indoor room air was inhomogeneous. Whereby, the results are different when deploying controlling sensors in various positions. Besides, this research intends to improve the effectiveness of the information management during building O&M. As the HVAC system influences the whole room once turned on, we assumed a linear relationship on the indoor temperatures between two different position. Hence, the relationship between the mean indoor temperature and the terminal temperature can be assumed as shown in Eq. 1.

$$T_{te}^{m} = a_{te} + b_{te} * T_{in} \text{ (Eq. 1)}$$

$$T_{bms}^{m} = a_{bms} + b_{bms} * T_{in} \text{ (Eq. 2)}$$

$$T_{bim\_bms}^{m} = a_{bim\_bms} + b_{bim\_bms} * T_{in} \text{ (Eq. 3)}$$

where

T_{in} = Mean indoor temperature (°C);

T_{te}^{m} = Measured terminal temperature (°C);

T_{bms}^{m} = Indoor temperature measured by BMS (°C);

$T_{bim\_bms}^{m}$ = Indoor temperature simulated by BIM-BMS integration (°C);

b_{te} = Unstandardized diffusion coefficients for the terminal temperature;

b_{bms} = Unstandardized diffusion coefficients for the indoor temperature measured by BMS;

$b_{bim-bms}$ = Unstandardized diffusion coefficients for the indoor temperature simulated by BIM-BMS integration;

a_{te} = Unstandardized diffusion constant for the terminal temperature;

a_{bms} = Unstandardized diffusion constant for the indoor temperature measured by BMS;

$a_{bim-bms}$ = Unstandardized diffusion constant for the indoor temperature simulated by BIM-BMS integration.

In most of the research, calculating the mean indoor temperature is involved in BPS (Lambie, Senave, Van de Vyver, & Saelens, 2017). By using the results obtained from BPS, the temperature simulated in the proposed system can be assumed as equal to the mean indoor temperature:

$$T_{bim\_bms} = T_{in}$$

As mentioned before, there are no benchmarks in measuring building performance in New Zealand (BIM Acceleration Committee, 2016). Hence, the only way is to compare the costs among different testing operation modes. In light of this, we conducted an indirect observation on the temperature measured by using a terminal sensor method, a single on-wall sensor method, and an optimized method. These data can represent the fluctuations of the mean indoor temperature measured by traditional HVAC, BMS-managed HVAC, and BIM-BMS integrated HVAC. Prior to collect the data, temperature sensors were deployed onsite. Once data obtained, the data will be analyzed in SPSS to calculate the unstandardized diffusion coefficients and constants. Specifically, for d independent variables, the number of required regressions is $2^d – 1$ (Luchman, 2014). To obtain the relationship between each couple of these three temperature streams, two independent variables for each linear regression analysis. Hence, the number of observations should be determined larger than $2^2 – 1 = 3$. Considering the outdoor temperature fluctuations, we determined to observe temperature data throughout a whole day (24 hours). Due to the thermal inertia of the temperature sensors, the observation interval was set as hourly based. Hence, the number of the observations was determined as 24 (W. Li, Yang, Ji, & Xu, 2019).

Despite this, the data obtained is of a single day. We generalized the results into a season-based while avoid being merged in a huge amount of observations. The operation was simulated in MATLAB by using the relationships identified. Wherein, the trends of energy savings based on a different time in the winter time (01/04/2017-30/09/2017) were plotted.

Towards comparing the different operation modes, the independent variables for the simulation were then determined as the room air temperature measured $T_{measured}$ among three scenarios. Wherein, (1) $T_{measured}$ = T_{te} in operation without BIM or BMS; (2) $T_{measured}$ = T_{bms} in operation with BMS; (3) $T_{measured}$ = T_{bim_bms} in operation with BIM-BMS integrated. Specifically, for d independent variables, the number of required regressions is $2^d – 1$ (Luchman, 2014). Hence, the number of measured streams was determined as $2^3 – 1 = 7$ streams. Whilst, the interval was set as hourly based.

To simulate the operation of the HVAC system in the three scenarios on the pilot case, we adapted our simulation models from the “thermal model of a house” established by The MathWorks (2018). In the first place, the heat flow into the room is expressed by the Eq. 4.

$$\frac{dQ}{dt} = (T_{heater} - T_{in}^{m}) \cdot Mdot \cdot c \text{ (Eq. 4)}$$

Where

$\frac{dQ}{dt}$ = Heat flow from the heater into the room;

c = Heat capacity of air at constant pressure;

Mdot = Air mass flow rate through heater (kg/hr);

T_{heater} = Temperature of hot air from heater (°C).

Then, heat losses and the temperature time derivative are expressed by Equation 2.

$$\left(\frac{dQ}{dt}\right)_{losses} = \frac{T_{in}^{m} - T_{out}}{R_{eq}}$$

$$\frac{dT_{in}^{m}}{dt} = \frac{1}{M_{air} \cdot c} \cdot \left(\frac{dQ_{heater}}{dt} - \frac{dQ_{losses}}{dt}\right)$$

where

M_{air} = Mass of air inside the house;

R_{eq} = Equivalent thermal resistance of the house.

On operating, the HVAC will be controlled by the thresholds (T_{min} to T_{max}) set. To put it into another way, the HVAC will start to heat when $T_{measured} \leq T_{min}$. Whereas, the HVAC will be turned off once $T_{measured} \geq T_{max}$.

Then, the $T_{measured}$ in the three scenarios will be inputted after calculated based on the real-world T_{out}. The operation costs *C* can be calculated based on the electricity price of New Zealand at the time be calculated. Therefore, the dependent variables are determined as the operating costs *C*. Once get the results of those three costs, the energy savings can be calculated separately for both the proposed system and the BMS alone.

4.8 Summary

This chapter emphasized on the complexity theory and the exploratory design research. In the first section, the suitability of adopting the complexity theory was discussed towards delivering a complex system. The solution for the research problem was identified as cross-discipline. This highlighted the efficient use of complexity theory in transforming the cross-discipline problem into a multi-discipline problem. Through the complexity theory, the entire system can be scaled into components. Given this, the behavior of each component will be identified by this study. Besides, the conceptual framework of the proposed system was established. The inputs, outputs, constraints, and tools were identified. Such a conceptual framework provided an overview of the solution to the research problem.

The remaining sections provided a sequential model for the work flow. The data collection phases for both qualitative and quantitative data were illustrated. A detailed description of data collection methods including documentation analysis, focus group interview, axiomatic design, agile development, and pilot testing were given.

Considering the research aim, the efficiency of the selected methods was demonstrated. In the first place, documentation analysis was used for clarifying the research base. Such method was used for delivering New Zealand specific terminologies. Then, to explore the New Zealand specific barriers coupled with potential solutions, the focus group interview method was identified as the most suitable method for filtering the general context into a New Zealand specific context. After that, the axiomatic design method was followed due to its high interoperability and flexibility. Likewise, the agile development also presented its flexibility to change. To generalize the research outcomes into wider use, this method was adopted for developing a working prototype following the proposed framework. Last, to validate the proposed system, a pilot test was the most efficient way to obtain empirical data.

Besides, two routes were given: data collection and demonstration. The data collection route will be followed in presenting the results whereas the demonstration route will be used when synthesis the results towards achieving the objectives. After determining the research methods, the next phase of this study was to present the research results.

Chapter 5 Results and Analysis from Documentation Analysis

5.1 Introduction

The purpose of this chapter is to clarify and discuss BIM terminology in order to achieve the objective of redefining the New Zealand specific BIM and its related terminologies (Objective 1). This chapter mainly deals with two aspects: in the coming section, the BIM definitions collected from the documents will be evaluated, and a New Zealand specific BIM will be defined. After that, BIM maturity levels will be clarified in a New Zealand context. Wherein, it is mainly hypothesized that: by the promotion of multi-project interaction, BIM will achieve the next maturity level: BIM Level 4.0. To examine this hypothesis, three sub-hypotheses are made more specifically as below:

(1) H_1: The barriers that are not expected to be handled at BIM Level 4.0 should not be able to be targeted at within BIM Level 3.0 directly; while achieving BIM Level 4.0 is a pre-condition for them.

(2) H_2: The main gap (G3) identified in BIM Level 3.0 can be feasible to be bridged once achieving BIM Level 3.0; however, G3 cannot be targeted directly at BIM Level 2.0 (or below) or bridging G3 cannot benefit at BIM Level 2.0 (or below).

(3) H_3: BIM 4.0 should be established to remove G3; by doing this, it will be expected to handle the main barriers at BIM Level 3.0.

5.2 Updated BIM Definitions

The rapid development of information technologies in the AEC/FM industry is consistently changing the definition of Building Information Modelling (Migilinskas et al., 2013). Currently, typical definitions include:

The National Building Information Model Standard, USA (National Institute of Building Sciences buildingSMART alliance, 2015):

> "Building Information Modeling (BIM) is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition."

National Building Specification, UK (NBS, 2016):

> "BIM or Building Information Modelling is a **process** for creating and managing information on a construction project across the project lifecycle. One of the key outputs of this process is the Building Information Model, the digital description of every aspect of the built asset. This model draws on information assembled collaboratively and updated at key stages of a project. Creating a digital Building Information Model enables those who interact with the building to optimize their actions, resulting in a greater whole life value for the asset."

Autodesk, Inc. (Autodesk Inc., 2018):

> "BIM (Building Information Modelling) is an intelligent 3D model-based **process** that gives architecture, engineering, and construction (AEC) professionals the insight and tools to more efficiently plan, design, construct, and manage buildings and infrastructure."

However, three inconsistent points for BIM definitions were found by this research:

(1) In the past, only design parameters were involved in a BIM model. These parameters paired with their 3D entities are digitally represented (National Institute of Building Sciences buildingSMART alliance, 2015). However, by the adoption of BIM in other lifecycles such as FM, the need for integrating analogical data are gradually improved. Hence, it is an urgent need to update the digital representation to a combination of both.

(2) BIM was a visualization for the AEC/FM information while it gradually becomes a process to construct, integrate and manage such visualization. Definitions made by NBS (NBS, 2016) and Autodesk Inc. (Autodesk Inc., 2018) are more suitable for the current applications than by the National Building Information Model

Standard (National Institute of Building Sciences buildingSMART alliance, 2015).

(3) Formerly, fewer projects made interaction to other projects in BIM; however, there is a need for the BIM definition to adapt to the inter-project dependency (Arayici et al., 2018).

Above all, this research made a redefinition for BIM orienting to BIM Level 4.0 as below:

Building Information Modelling is a process of creating, sharing, exchanging, integrating, and managing digital and analogical representations with multiple dimensions, in multiple disciplines, by multiple stakeholders, at multiple lifecycles, for multiple projects.

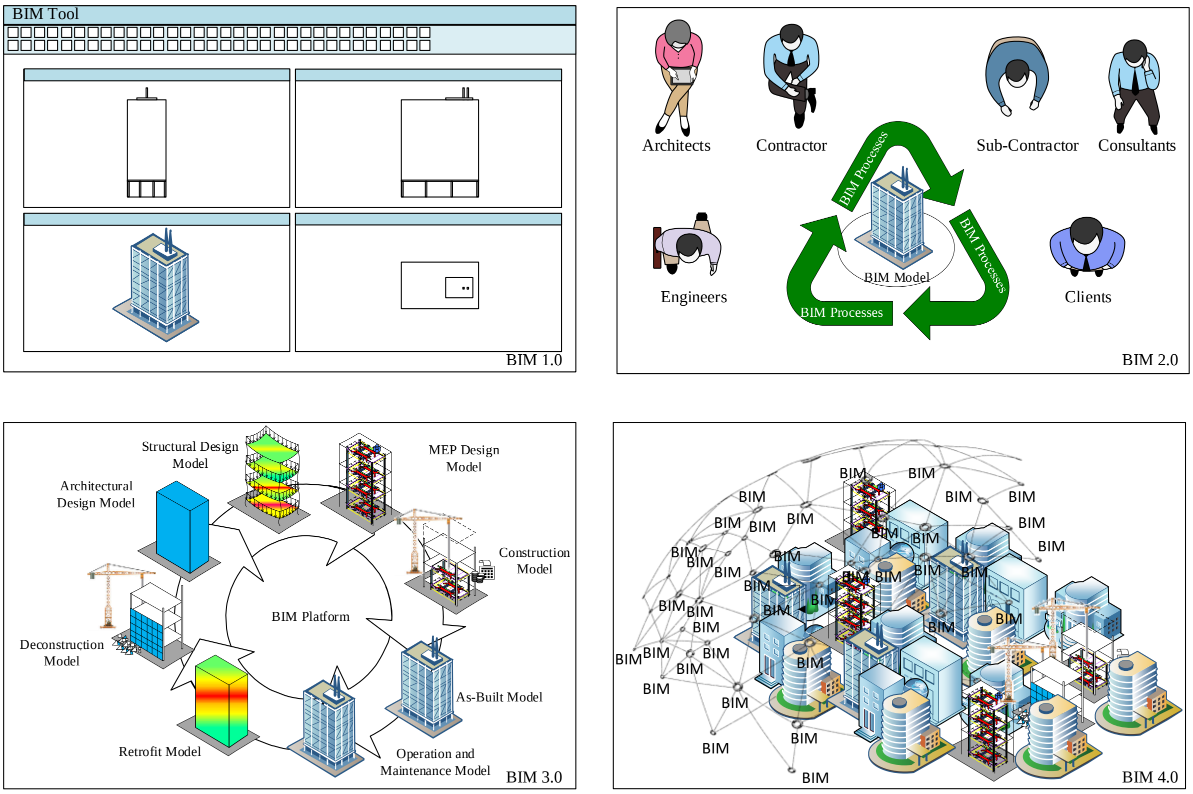


Figure 16 BIM Implementation in Different Maturity Levels.

5.3 Updated BIM Maturity Levels

This study investigated the potential role of BIM in proposing inter-project interoperability. To our knowledge, it is the first study that investigates the effect of BIM beyond the traditional BIM practices at 1-3 levels. There was a significant correlation between the BIM levels resulted in this study and NBS's BIM maturity levels. Upon the NBS's BIM maturity levels, we refine BIM Level 0.0-3.0 while establishing a BIM Level 4.0 (See Figure 16 and Figure 17):

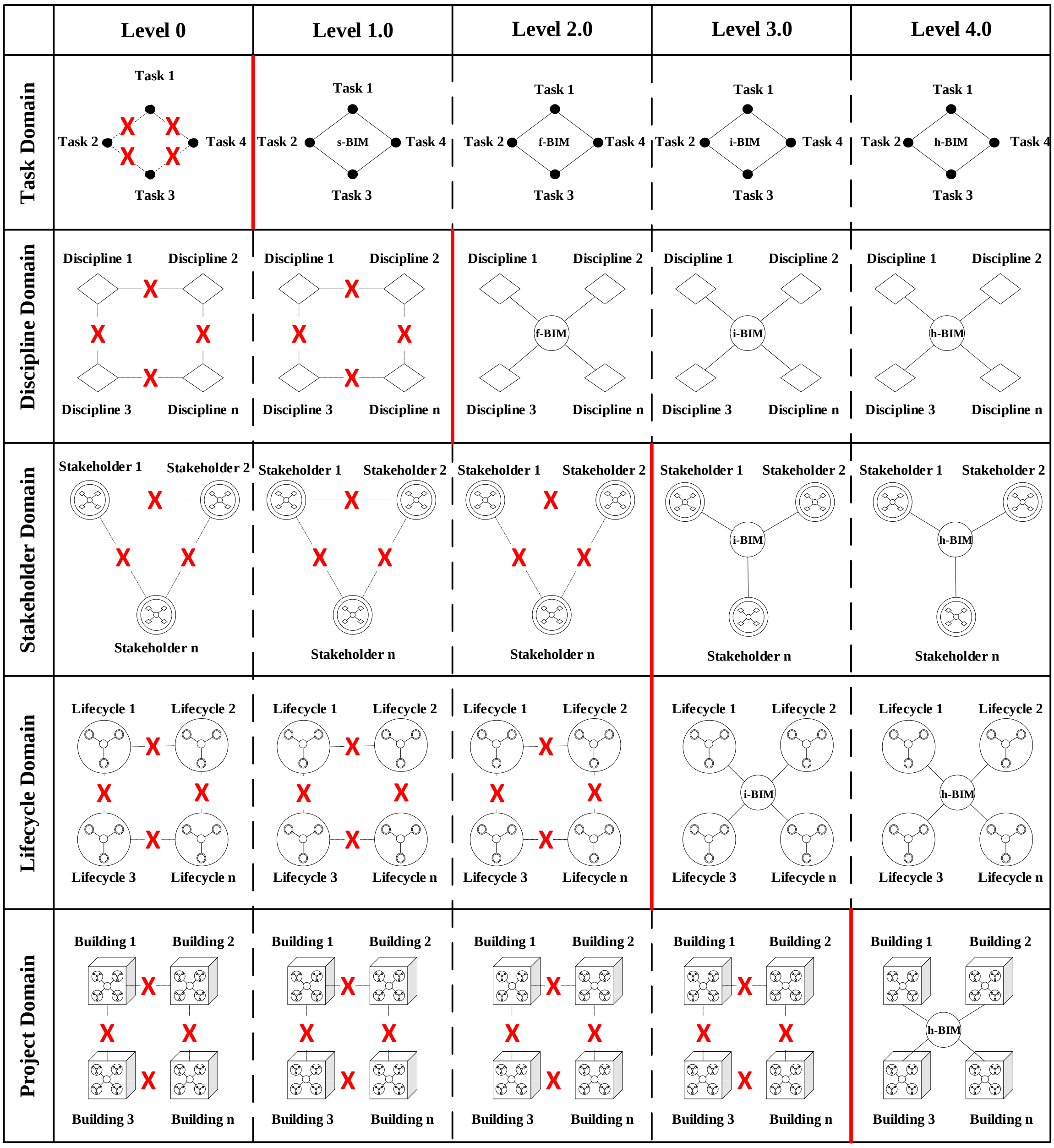


Figure 17 the BIM Maturity Mechanism.

(1) BIM Level 0.0.

Refer to NBS, BIM Level 0 adopts the conventional CAD workflow for AEC/FM projects. Similarly, our BIM Level 0.0 refers to a level that outputs in the same discipline are made separately, and once one changes, the corresponding outputs cannot be updated automatically. By contrast, we allocate 3D CAD to facilitate multi-task responsiveness in the next level while remaining instrument sketching and 2D CAD at this level.

(2) BIM Level 1.0.

Before BIM actually executes, multi-dimensional information framework should be conceptualized. In almost all the contexts, BIM was first promoted in the design phase. That is because BIM models are most commonly generated during design while most visualized 3D benefits have been observed in this phase. Hence, BIM Level 1.0 refers to a level that outputs in the same discipline are responsive to each other, and there are no gaps within one discipline, however, gaps exist among different disciplines.

Traditional instrument sketching fails to make full adaptive control among different tasks in one discipline. Once a 3D CAD/BIM tool is adopted, draftsmen can export various drawings within a single-discipline 3D model. Towards this end, requirements stated in NBS BIM Level 1 should also be satisfied in our BIM Level 1.0: a clear role paired with its responsibilities, well-naming conventions, code and spatial coordination arrangement, a CDE, and a well-defined document repository in place. Despite this, interference among disciplines exist.

(3) BIM Level 2.0.

Towards an efficient design, a BIM is expected to facilitate the multi-discipline federation in the design phase. However, at this level, BIM is not limited in design models. By frontloading construction people, 4-5D simulation models are created as well. Hence, BIM Level 2.0 refers to a level that people in one team can federate multi-dimensional works in all disciplines together. In comparison, NBS involved multi-dimensional BIM, especially 4D scheduling, and 5D estimation, for multi-discipline coordination in its Level 2. This is consistent with our results.

(4) BIM Level 3.0.

NBS described this level as a fully collaborative level. They noted that BIM Level 3 enables all parties' accessibility and lifecycle management beyond BIM Level 2. In the BIM maturity description by Wiki (2018), BIM level 3 was described as "a single, collaborative, online, project model including construction sequencing, cost and lifecycle management information". While HM Government (2015) released an updated BIM level 3 strategy – digital built brain. Such strategy identified the capacity of the cross-sector collaboration of BIM in BIM level 3. This collaboration includes people, power, water, transportation, buildings, etc. However, it can only be achieved when a sufficient amount of existing buildings has BIM models that meet the requirements of cross-sector data exchange. Provided that the UK government mandated BIM adoption while almost all of the other counties not, such as New Zealand (BCPP, 2016), etc. That said, the New Zealand context might not have enough models for existing buildings even if they have already been mature in practicing single project delivery in BIM level 3.

With this in mind, rather than completely introducing cross-sector collaboration into the BIM Level 3.0, we prefer to divide it into two aspects for BIM Level 3.0 and 4.0 separately. They are the model capacity and the number of models. A "fully collaborate" BIM model might integrate enough information that is capable for the purpose of cross-sector collaboration, then again, in BIM level 3.0, sufficient amount of BIM models for existing buildings is not a must. That is, our BIM Level 3.0 is redefined as a level that people from all stakeholders are able to collaborate in all discipline works in a multi-dimensional repository throughout the whole lifecycle.

(5) BIM Level 4.0.

Giving a fully collaborative BIM in Level 3, NBS did not present a BIM Level 4 definition. Nevertheless, full collaboration is a means to an end, not an end in itself. As given above, at this level, sufficient BIM models will exist, which establish the Internet of BIM (IoB). BIM is potential to further inter-project interoperability beyond a single project lifecycle management. Hence, our BIM Level 4.0 refers to a level that BIMs from multiple projects are interconnected, which enables the interaction in knowledge, spatial, economic, society, industry, etc.

Therefore, in a New Zealand context, the "BIM Wedge" is updated (See Figure 18), and the maturity levels are shortened as non-BIM (n-BIM), standard BIM (s-BIM), federal BIM (f-BIM), integrated BIM (i-BIM), and holistic BIM (h-BIM).

As mentioned in the results, a lack of interaction among multiple BIMs has been observed as a gap in BIM Level 3.0 (G3). This gap cannot be bridged until all the corresponding projects have successfully delivered a single project BIM outcome. All of the studies reviewed in this study support the hypothesis (H_1) that G3 can be feasible to be bridged once achieving BIM Level 3.0; however, G3 cannot be targeted directly at BIM Level 2.0 (or below) or bridging G3 cannot benefit at BIM Level 2.0 (or below).

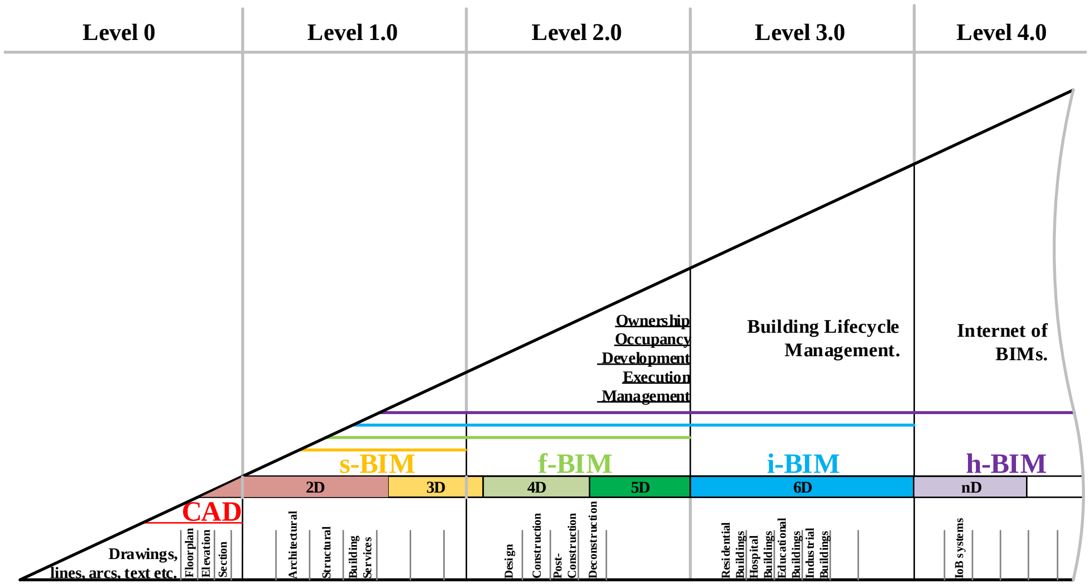


Figure 18 the Updated "BIM Wedge".

For a larger scale of BIM use, a smart city can be achieved with a range of BIM models (Heaton & Parlikad, 2019). There is a growing body of literature that recognizes the importance of smart city (Ciribini et al., 2017; W.-L. Lee et al., 2016; Ma & Ren, 2017; Teo & Cho, 2016; Yamamura, Fan, & Suzuki, 2017), CIM (Deng et al., 2016). However, confusion exists among BIM Level 4.0 and those terms. All of those terms are featured in a multi-project pattern. “Smart city” is a vision to integrate multiple Information and Communication Technology (ICT) and the IoT solutions securely to manage a city’s assets (Ma & Ren, 2017). It interconnects a range of Intelligent Buildings (IB) makes it possible to reduce cost and energy consumption by efficiently managing and controlling facilities throughout building automation systems (BAS) (W.-L. Lee et al., 2016). Although extensive research has been carried out on the use of BIM on developing a smart city (Borrmann & Rank, 2009; Cerovsek, 2011; Isikdag et al., 2008; Isikdag et al., 2007; Isikdag, Zlatanova, & Underwood, 2013; Langenhan, Weber, Liwicki, Petzold, & Dengel, 2013; G. Lee, Park, & Won, 2012; Yan, Culp, & Graf, 2011), the use of BIM is always limited within Asset Information Models (AIM) in a city scale. In contrast, by achieving BIM Level 4.0, the interconnection of BIMs is expected to go throughout all building lifecycle phases.

On the other hand, CIM is a series of BIMs in urbanism scale. It combines BIM and Geographic Information Systems (GIS) to proceed with information management and carry on a variety of simulation (Isikdag et al., 2008). This model will be limited within a specific area, like a city, a town, or a community. In comparison, IoB is proposed to involve all the buildings on a global scope. However, different IoB systems might be independent of each other, which is a further BIM maturity level beyond BIM Level 4.0 should target on. Before BIM Level 4.0 achieved, such IoB systems are not existing, which makes it impossible to target on the integration of different IoB systems. Therefore, these results provide significant support for the hypothesis (H_2) that the barriers that are not expected to be handled at BIM Level 4.0 should not be able to be targeted at within BIM Level 3.0 directly; while achieving BIM Level 4.0 is a pre-condition for them.

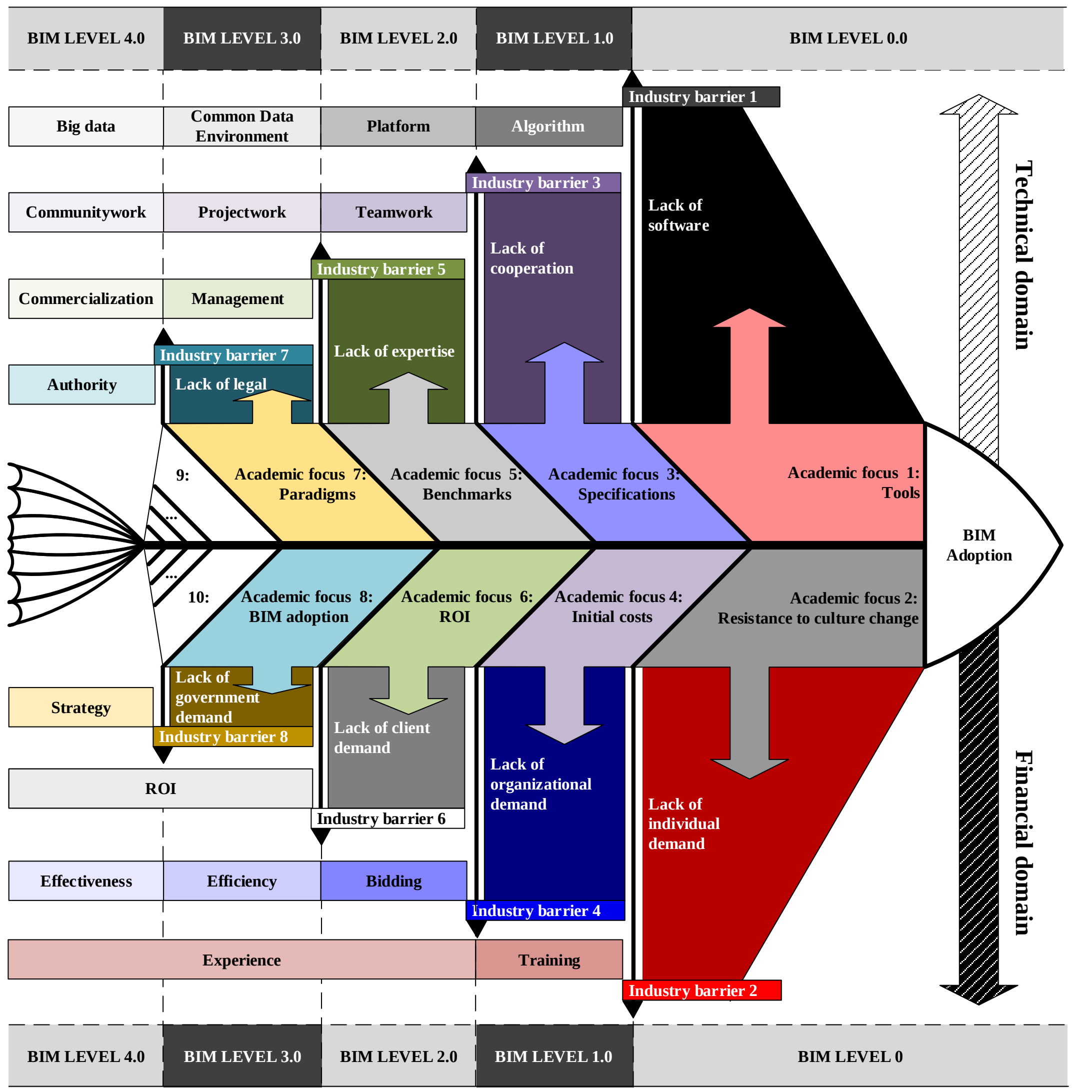


Figure 19 Barriers in BIM Adoption.

After WFB analysis by year, a positive correlation was found between academic focuses and industry barriers. Academic focus is usually progressed faster for one level than the industry practices. Nonetheless, the same barrier can be within different contents in different maturity level. In light of the academic focus in publications from 1975-2018, we have a better understanding that the BIM is changing.

The academic focuses are grouped into technical and financial domains while the corresponding barriers are illustrated in Figure 19. In the technical domain, research has been carried on in tools, specifications, benchmarks, and paradigms. Initially, the lack of a software barrier existed since BIM was born.

Then, in BIM Level 1.0, basic algorithms were developed to facilitate 3D visualization, crash detection, etc. to facilitate people separately. Due to the essence of this level, a lack of cooperation urgent the need of precise specifications.

After that, numbers of BIM platforms embraced the BIM Level 2.0 and provided a shared model for team works. However, a lack of benchmarks increased the risk for project failure, and fewer expertise in BIM coordination aggravated this situation at this level.

When it comes to BIM Level 3.0, CDE was provided to those tools towards managing a shared project repository. Despite this, legal issues became the main barrier for sharing and using the BIM models among different parties.

Finally, the legal was well defined so that BIM models from different projects were able to be appropriately interconnected. Importantly, big data issues in those tools should be solved to make it possible to the higher level of BIM use -- IoB. This finding, while preliminary, suggests that the barrier in BIM Level 3.0 is identified as legal issues. Before achieving BIM Level 3.0, legal conflicts are not intense, because they are expected to be resolved with the interference from the project owners. Once proposing a multi-project interaction, they cannot be resolved without legal policy.

On the other hand, the financial academic focus includes resistance to culture change, initial costs, ROI, and BIM adoption. First, when BIM was first introduced to the AEC/FM industry, a culture change for the engineers was made. However, a lack of individual demand became the resistance.

Next, by using proper BIM tools in BIM Level 2.0, the individuals were likely to improve their efficiency in their daily tasks. High initial costs raised the barrier on demand from organizations, including training, software, and hardware costs.

Then, the clients were engaged in BIM Level 3.0. However, they did not see any tangible benefits of BIM in their ROI. By the successful implementation of building lifecycle management, the clients were able to see the proven good ROI on BIM. However, various clients from different projects were not interconnected without the government promotion.

Last, the IoB might only be achieved when the government demand was met. Thus, the leading financial barrier in BIM Level 3.0 is the lack of government demand. Although government policy on BIM has made some effective accelerations on BIM adoption, it cannot be the main barrier before BIM Level 3.0.

In the financial domain, it is the demand from individual, organization, and client that mainly drive the development of BIM at BIM Level 0.0, 1.0, and 2.0. Taken together, these results suggest that the main barrier in BIM Level 3.0 is the lack of legal issues and government demand, which is a pre-condition of achieving BIM Level 4.0. This finding supports the hypothesis (H_3) that BIM Level 4.0 should be established to bridge G3 identified in BIM Level 3.0. By doing this, it will be expected to handle the main barriers at BIM Level 3.0.

5.4 Summary

This chapter presents the outcomes and findings of the documentation analysis gained from the main academic database. The findings answered the investigating questions (Q1-Q3) proposed in this study. The findings suggested that the current BIM definitions paired with BIM maturity levels were not sufficient to provide a clear research base for examining BIM in the New Zealand context. Facing these issues, this chapter provided a New Zealand specific definition of BIM. Meanwhile, the BIM maturity levels were refined in a New Zealand context. Based on the data analysis all hypotheses were accepted which means the maturity levels are efficient to represent the BIM adoption process in

New Zealand. In addition, the barriers for each level were obtained separately. The outcomes were expected to eliminate the disputes in New Zealand BIM research. In the coming chapter, results from the focus group will be provided in details.

Chapter 6 Results and Analysis from Focus Group Interview

6.1 Introduction

The purpose of this chapter is to indicate the current barriers towards a BIM-BMS integration managing existing educational facilities in New Zealand (Objective 2). The results from the focus group interview will be examined. In the coming section, the relationship between BIM and BMS will be discussed. In the third section, the current BIM adoption in New Zealand will be evaluated from an industry perspective. The fourth section will examine the significance of the BIM-BMS integration in terms of supporting FM in New Zealand. Following this, the limitations for the BMS and the BIM-BMS integration will be analysed separately. Thus, the specific barriers coupled with specific suggestions can be obtained.

6.2 BIM-BMS Relationship

> Question 1: What is the relationship between BIM and BMS? Is BMS a part of BIM?

The first question aimed to investigate the industry understanding of BIM, BMS, and their relationship. In response to the question, a range of answers were elicited. All agreed that BIM and BMS are totally different things hence BMS is not a part of BIM at all. They held that BIM is used for documentation while BMS focuses on the building performance. Nevertheless, it was suggested that BIM should deliver information to the BMS. Interestingly, a facility manager panelist noted that BMS is a smaller subset function of a lager BIM process model. This will generate fresh insight into a discussion between the macro BIM and the micro BIM. However, the majority of participants (4/5) agreed with the statement that, at this point, there is no real traction around the concept of BIM, BIM as a process, or BIM as an output in New Zealand.

6.3 BIM Adoption in New Zealand

> Question 2: What do you think about the BIM adoption in New Zealand? Is it fully used?

The purpose of this question was to re-evaluate the BIM adoption in New Zealand. The overall response to this question was very negative. When asking about the BIM adoption in New Zealand, they noted that the BIM adoption rates for operation in New Zealand in those surveys are true and stable. However, it is hard to change. Nevertheless, all agreed that BIM is not fully used by a long way in New Zealand.

One panelist mentioned that there might be a number of flagship construction projects declaring the use of BIM beyond the construction practical completion phase. However, how this is applied and where this additional outspend creates tangible operational efficiencies leading to commercial benefits have not been validated. This view was echoed by another panelist who indicated that, currently, BIM in New Zealand is just about a few showcases. Those BIMs are only used for digitalization, specifically documentation. Yet their models have never been used by the operator in New Zealand. These responses suggest that BIM in O&M is immature in New Zealand. Additionally, there are no BIM software solutions for building O&M. In light of such conditions, one panelist from asset management emphasized that there is a market to push BIM into the operation phase. This view was resounded by the other panelists in the roundtable.

6.4 Significance of BIM-BMS Integration

> Question 3: Is the significance of BIM-BMS integration in supporting facility management in New Zealand?

When asked about the value of BIM in the building O&M phase, the participants were unanimous in the view that, currently, there is no value proposition for an operator of going the extra mile (and cost) to operate and maintain a fully integrated BIM model. Likewise, over half of them (3/5) also mentioned that BIM makes sense in the design and construction phases in New Zealand, while no real-world evidence shows that BIM benefits the O&M phase.

Interestingly, one panelist from a BMS provider company stated that existing BMSs in New Zealand are sufficient to operate the building without the help of BIM. In contrast, a BIM consultant panelist argued that BIM potential exists with the function of 3D visualization and documentation in the building operation phase. It might be more convenient to navigate a BMS linked to condition and maintenance history data within a pictorial format.

The other panelists (3/5) felt that bridging the gaps between BIM and BMS can get BIM onto a further maturity level. They mentioned that numbers of materials online they had read supported that BIM is valuable for BMS towards a more efficient FM. However, the majority of those (4/5) indicated that there is no successful integration of BIM and BMS in New Zealand. Notwithstanding, just over half of them (3/5) remarked that with a more mature BIM, the proposed BIM-BMS integration would be expected to support FM in New Zealand.

There were some suggestions that it will be easier for the operators in decision-making by comparing the BMS data with design objectives in BIM models. To achieve this, facility operators should be upfront in the early design phases. Also, a variety of scenario modeling should be made in the design and construction phases. Meanwhile, it was also suggested that with efficient utilization of space, appliances paired with performance measuring, the operators are expected to identify what’s working, what’s performing quickly. Another reported problem was that the value of BIM for FM is not easily explainable or sellable, and it's not quantifiable. One panelist suggested to compare the building operation with a traditional one. Due to the large variety of buildings in types, scales, and locations, there are currently no benchmarks for O&M in New Zealand.

6.5 Limitations for BMS without BIM

Question 4: What are the current limitations for BMS without BIM?

The fourth question in the panel was to identify the limitations in current BMS in New Zealand which is potential to be addressed by the adoption of BIM. A number of themes were identified from the responses to this question including cost, change management process, big data and lack of intelligence. In terms of cost the panelist from the asset management company indicated that the ROI of installing BMS is not clear. The initial outlay for BMS is high, while the savings in O&M phase are not easy to be measured. Another panelist on FM stated that the costs for O&M are usually different from what been designed.

Even if validated, the building owners do not want to spend money on those savings as the tenants pay for that change management process. The overwhelming majority of the panelists (4/5) emphasized the update and maintenance for BMS itself. The panelist from the asset management company reported that change management process is missing in FM in New Zealand. As time goes after occupancy, human interactions on the facilities keep on conducting. That is to say, the BMS will perform inconsistently. Also, retrofits will also contribute to such change. Hence, if something is changed, the operators have to update it in BMS.

In terms of big data, the panelist from the BMS provider gave an example that there were around 35,000 data points generated per hour in one of the building projects that he worked on. Before the operation of this BMS, the alarm was set unwisely. Provided that the operators had to confirm and close it once BMS alerted. When the BMS started to operate 24 hours 7 days per week, the operators will be merged in a huge amount of alerts. Other panelists agreed with him and indicated that there is a tendency to abuse BMS. Too much noise exists for the processes. They suggested that data interval for real-time monitoring should be set accurately.

The final theme was the lack of intelligence. It is generally agreed that with a BMS, a building can be smart. Surprisingly, the panelist from the BMS provider expressed concerns that there is no intelligence in BMS. Refer to his knowledge, BMS is a control system which takes actions only based on the inputs. Such a control system is limited in responding to the scenario when something is mechanically wrong. Having said that, a minority of the panelists (2/5) indicated that, currently, most of the BMSs for HVAC in New Zealand operate with a daily schedule. Such systems even work during the weekends when no one there. Provided that, two HVAC in the same room might be heating and cooling separately at the same time.

6.6 Limitations for the BIM-BMS Integration

Question 5: Why current BIM-BMS cannot meet the expectation from the stakeholders?

To identify the barriers to proposing BIM-BMS integration, the panelists provided some realities they faced when proposing BIM or BMS. There were some negative comments about the use of BIM in New Zealand. A common view amongst the panelists was that the BIM-BMS integration is theoretical and not practical. Some (3/5) felt that the BIM and BMS readiness should be considered before implementing BIM-BMS integration, while others (2/5) considered that the investment on BIM in the operation phase could hardly get back.

Regarding BIM and BMS readiness, they expressed concerns about the current immature product, process, and people (PPP). In terms of product, there are no BIM software solutions for building O&M. One panelist added that designers use BIM software solutions for making their job easier but never been designed with consideration from an end user perspective. The panelist from asset management company gave an example from his experience that facility manager often gets a USB stick with a BIM model when construction handover, while no concepts about how they use the BIM model and keep it up to date. Another panelist commented that BIM is truly silo.

Another key thing to remember, predictive modeling hasn't been integrated to BIM in New Zealand. The panelist from the BMS provider reported that facility managers in New Zealand do not need to make preventive maintenance while they just repair the facilities. However, one panelist from asset management argued that the need for preventive maintenance depends on the assets. Having said that, BMS is not reliable. Referred to the panelist from the BMS provider, currently, there are massive numbers of protocols in serial communication. Significantly, those protocols should be normalized into ISO communication protocols. The proposed products also suffer from software versioning. It is difficult to normalize those two anomalies - BIM and BMS in different versions separately. Another reported problem was that even the gaps between BIM and BMS been bridged, benefits from it are still not clear. The majority of the panelists (3/5) cannot see how the proposed system can be equally as effective as in a numerical or tabular format for outlay and ongoing management.

When discussing people, concerns were expressed about that the BIM-BMS integration is not scalable as it needs both BIM and BMS knowledge. In this stage, facility managers in New Zealand struggle to manage the BMS. Provided that, bringing another complexity - BIM, on top of it makes it more difficult. Having said that, BIM models are not established from an end user perspective. Such models can only be used for building design and construction.

In terms of process, the BIM-BMS integration is technically difficult and financially expensive. There was a common sense among the panelists (5/5) that the only way for

BIM-BMS integration is upfront. However, in New Zealand, FM is not involved in building design and construction processes. What's worse, the margin costs in the early stage are very small or non-existent. On the other hand, existing buildings might not have BIM models. In the latest years, BIM technology struggled to be adopted in New Zealand. That is to say, only a few new buildings in New Zealand have their BIM models established. Providing that, a large amount of funding will be needed for this purpose.

When talking about the costs, the high initial costs for modeling and the long-term maintenance costs for such models were identified as one of the biggest roadblocks by the panelists. Several issues were identified regarding the costs for the BIM-BMS integration. First, high initial costs will be a barrier to the BIM-BMS integration adoption. As mentioned before, modeling a BIM in the operate phase is not cost-effective. Besides, the people who operate will not get payment from the energy savings. As what the panelist from the asset management company suggested, they are box thinkers. That is to say, they usually get a timeline paired with a budget to make things happen. Those budgets cannot be obtained from the savings from lifecycle management. Hence, the end users do not like to fund the initial costs. However, one panelist gave an example of a data center building project to support that whole lifecycle value is significant. A balance between initial costs and whole lifecycle value should be made.

Second, keeping BIM models up-to-date is a cost driver. Assuming commissioning right, the operators are expected to obtain a close to 100% operational BMS. From time on, operators keep on making changes unknowingly and just for convenience: they break linkages and change settings. For example, they change the chiller setting due to a high temperature but don't change back. A time after occupancy, the proportion of BMS will be decreased. In other words, analysis is inconsistent. Likewise, the assets are changing without updates to BIM. Hence, a data manager is needed to maintain BIM models up to date.

6.7 Summary

This chapter presents the outcomes of the thematic analysis gained from the focus group interview. The findings answered the investigating questions (Q4-Q8) proposed in this study. As discussed in the focus group interview, BMS is possible to be involved in the macro BIM process. This made the evaluation process complex. The BIM adoption in New Zealand is still early while BMS has been used for years. Nevertheless, no BIM-BMS integration has been made in New Zealand. Not to mention the well-recognized big data issues, current BMS in New Zealand was mainly limited with a lack of intelligence. To achieve an intelligent BMS, BIM is a pre-condition. However, the immature organizational readiness in New Zealand industry becomes the roadblock of current BIM-BMS practices.

Chapter 7 Results and Analysis from Function Design

7.1 Introduction

Towards enhancing the building O&M effectiveness in New Zealand, building sustainable performance inspection and optimization during post-construction stage has become more and more critical. In spite of this, traditional O&M processes suffer from erroneous inspections and fragmented data input. Potential solutions collected from the focus group interview show that developing a KBS assisted BMS application based on nD BIM is expected to improve the performance of the proposed solutions. As discussed before, combining KBS, BMS, and BIM is anticipated to deliver two working modes: automatic fault detection and isolation, and simulation-based supervisory control.

Upon the conceptual model, the purpose of this chapter is to establish and verify the proposed framework, focusing on functional modeling towards accomplishing Objective 3. This study conducts based on the axiomatic-design principles. And develops the proposed framework using SADT language and IDEF0 diagrams. To establish a complex system with high flexibility, this study took the evolution for each module into consideration and identified the mutual interactions. Eventually, this study delivers a variety of 3-hierarchical IDEF0 diagrams in details. Those diagrams outline the proposed framework for implementing nD BIM-IKBMS. This research investigates the capability of the proposed system on reducing energy consumption, and utilizing historic retrievals and intelligent controls in building O&M. The efficiency of the proposed system was verified through the Independent Axiom.

The coming sections in this chapter are outlined as followings: the framework formation was the following part. The proposed framework will be modelized into numbers of parts. The interactions between different parts paired with the evolution behavior for each part will be identified in this section. After that, the interoperability and the flexibility of the proposed framework were verified.

7.2 Framework Formation

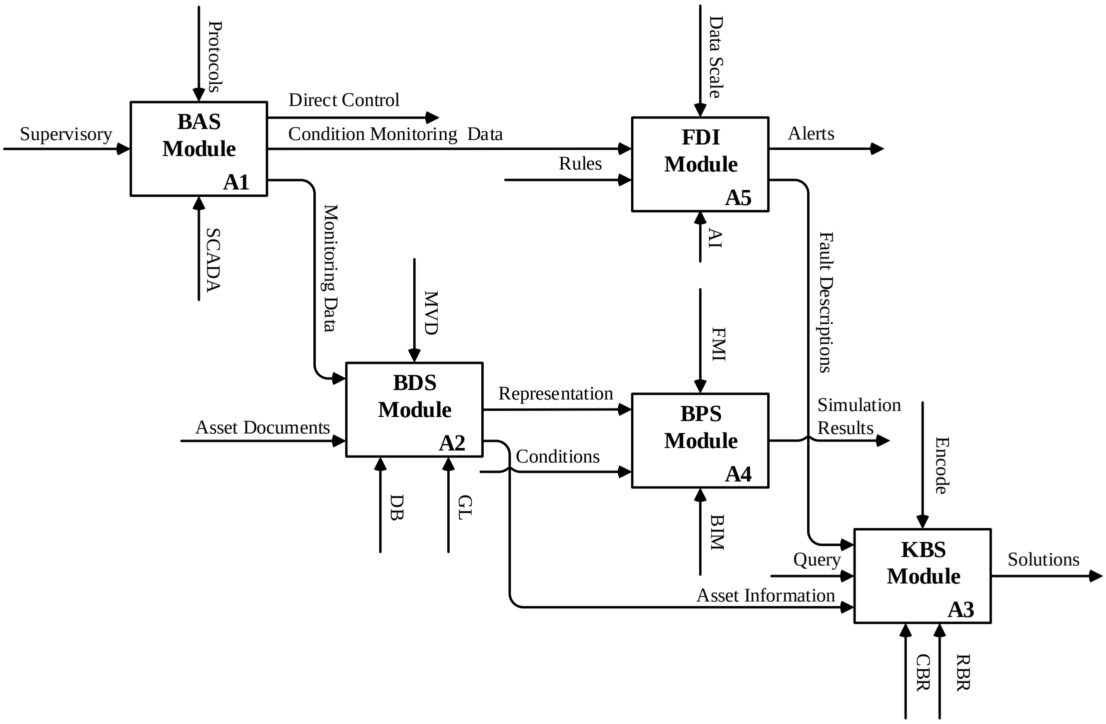


Figure 20 A0 ND BIM-IKBMS Module Division.

The proposed ND BIM-IKBMS (A0) has five modules (See Figure 20). They are:

(1) A1 BAS Module.

A1 module was developed based on a SCADA framework. Such framework includes a variety of BASs. The function of this module was developed. The end user sends supervisory commands to this module. Then, this module sends direct control comands to its appliances. Communication between any two parts must adopt same communication protocols. When the proposed system operates, the facility will send the monitoring data to the FDI Module.

(2) A2 BDS Module.

The A2 module follows the facility documentation methods. This module utilizes graphic libraries as well as database technology. The end user inputs the asset information into this module. To improve the interoperability, this module must be developed under the IFC standards.

buildingSMART International Ltd. (2018) defined that, “Industry Foundation Classes (IFC) are the open and neutral data format for openBIM”. The IFC format is an official International Standard ISO 16739:2013 registered by International Organization for Standardization (2013). Based on the IFC format, the building information can be accessed by A3 and A4 modules. Such information includes the asset documents as well as the digital model.

(3) A3 KBS Module.

Based on KBSs, the A3 function was allocated. Two main KBS types are used in this research. They are: RBR (Rule-Based Reasoning) -based and CBR-based. Both of these two types retrieve solutions by using KB languages. While, there are two queries: the automatic queries from A5 FDI Module and the end user’s manual queries. Provided that, the automatic queries must be formated for fault description. The reasoning efficiency of the proposed system can be enhanced. To promote the efficiency of such retrieval, asset information is obtained from A2 Module.

(4) A4 BPS Module.

Upon traditional BPS applications, The A4 function was established. Provided that, a 3D model is popularly used in building performance analysis. In this regard, BIM models can be used for better visualization. The modelling costs can be largely reduced by using the BIM models created in A2 module. With a purpose of decision-making in O&M, the end user can take advantage of the simulation results. Espectially, the end user can exchang the simulation results among various software. Such process was done by using standard interfaces.

(5) A5 FDI Module.

Based on the traditional FDI solutions, A5 function was established. The end user can take AI algrithms to make fault detection. Such algrithms can recognize the faults from coupious amounts of data from A1 module. Before the system operates, the end user should design the rules. When fault appears, the end users will be alerted by this module. The fault descriptions will be sent to the A3 module once the end user make similar case retrievals.

7.2.1 Building Automation System (BAS) Module

This module followed a SCADA framework. Such framework can achieve a supervisory control. When developing the proposed framework, four SCADA levels were used. They are: monolithic, distributed, networked, and IoT-based. Following different SCADA frameworks, the proposed system can get different operative behaviors.

(1) A1 BAS Module (Level 1 Monolithic).

At the monolithic SCADA level, the proposed module adopts a “mainframe” system with no networks. Wherein, each working prototype is independent. Also, different RTU vendors have different proprietary protocols. Such difference constrains the efficiency of the proposed system. The devices of this module can be categorized into two groups: A11 SCADA Master Sub-Module and A12 RTUs/PLCs Sub-Module. The master can acquire monitoring data from sensors. And it can also report the condition monitoring data to the end user. In addition, the terminal device operates with a direct control of its appliances. What’s more, the terminal device can send feedbacks to the A11 SCADA Master.

In spite of this, a proprietary adapter or controller can plug into the CPU backplane. This allows the A11 sub-module be connected at the bus level. The division of the A1 module is illustrated in Figure 21. All parts within these sub-modules interact mutually inside. This makes the sub-module not independent inside: it can not be divided further.

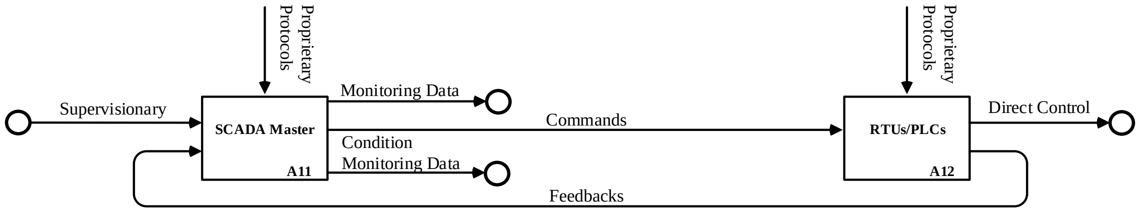


Figure 21 A1 BAS Module (Level 1 Monolithic) Sub-Module Division.

(2) A1 BAS Module (Level 2 Distributed).

The proposed system then will follow a “distributed” system once the Monolithic one evolves. Assisted by Local Area Networking (LAN) technology and system miniaturization, the proposed module will be distributed in multiple systems. Multiple A11 stations were connected through a LAN. This makes the proposed module capable of conducting a real-time information sharing. A11 stations have their own functions. And they communicate with their A12 module paired with their A13 sub-module.

In the meantime, by making the system more redundant, the system reliability is improved. If one station fails, another station can be used to operate the system. As a result, processing power requirements have been increased by such distributed networks. In addition, various RTU protocols only limits the external communications networks. In other words, the BAS module at this level is still constrained by vendor-controlled proprietary environment. The division for the proposed module is illustrated in Figure 22. All parts within these sub-modules interact mutually inside. This makes the sub-module not independent inside: it can not be divided further.

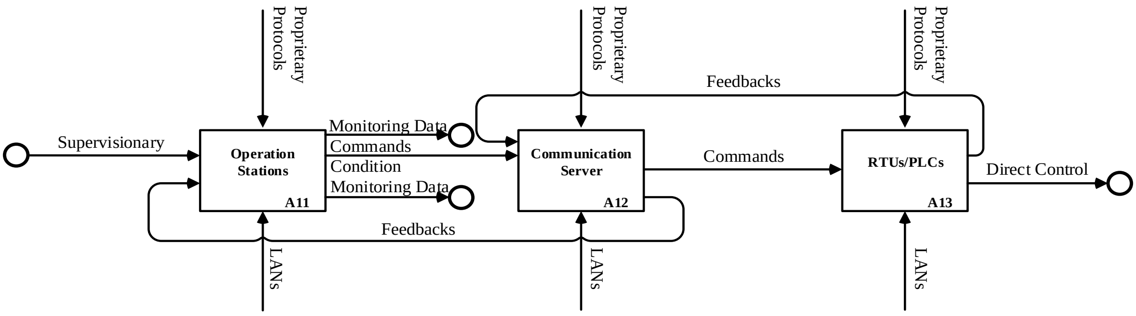


Figure 22 A1 BAS Module (Level 2 Distributed) Sub-Module Division.

(3) A1 BAS Module (Level 3 Networked).

Faced with the above problems in the distributed SCADA, a Networked module is prefered. Compared with previous products, the proposed system adopts an open system architecture to eliminate the limitations of multiple vendors. The proposed module deploys SCADA capabilities over a wide area network (WAN) using open standards and protocols. Through WAN, A14 is directly connected to the A11. Yet, vendor-proprietary RTUs still exists at level 3. On conditions that, A12 is still used to communicate with such RTUs. Furthermore, such module will distribute the processing into several individual physical locations. This makes the proposed system more reliable. As previously it stores data in a single location. The division of the A1 module is illustrated in Figure 23. All parts within these sub-modules interact mutually inside. This makes the sub-module not independent inside: it can not be divided further.

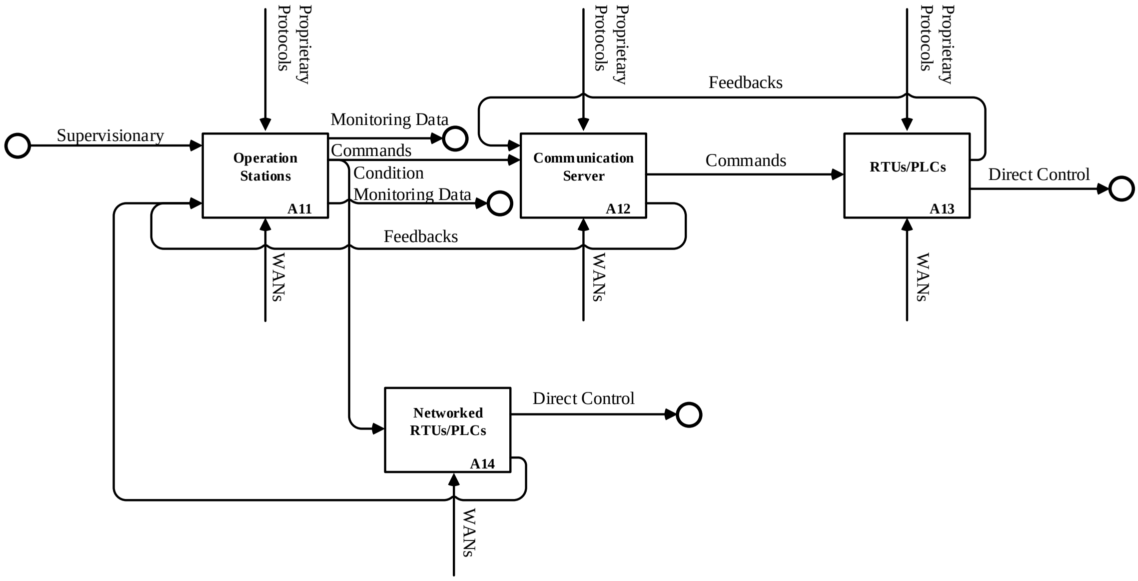


Figure 23 A1 BAS Module (Level 3 Networked) Sub-Module Division.

(4) A1 BAS Module (Level 4 IoT-Based).

An evolution based on the Internet of things is underway to bring this module to a higher level. At such level, the operation station is replaced by A11, with all vendors adopting the iso protocol. This protocol is the pre-condition for communication between devices. Hence, A11 can communicate with either A12 or A13. With a consideration of privacy, A12 is used for configuring additional settings. Furthermore, the condition monitoring data can be maintained for fault detection. The division of the A1 module is illustrated in Figure 24. All parts within these sub-modules interact mutually inside. This makes the sub-module not independent inside: it can not be divided further.

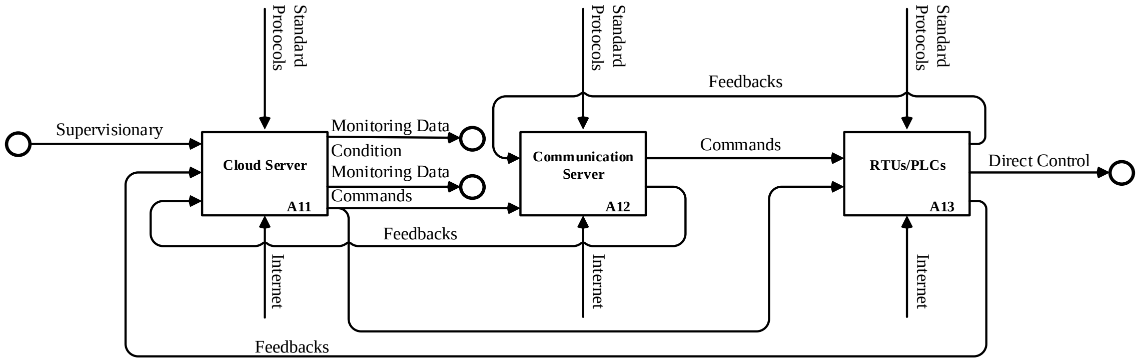


Figure 24 A1 BAS Module (Level 4 IoT-Based) Sub-Module Division.

7.2.2 Building Description System (BDS) Module

A documentation framework is designed for asset management. It provides digital representation for A4. As this framework evolved, there are three levels of documentation in the industry. At different levels of documentation, the proposed system can be associated with different operational behaviors.

(1) A2 BDS Module (Level 1 Flat Files).

To store the asset document, the proposed system adopts flat files at the level 1. Following this method, A21 has limited internal hierarchy. It is inefficient to retrieve the information. To constrain this module, flat files database specifications are adopted for MVD. Images are documented by using pixel-based graphic tools. At this level, merely 2D information is modelled. That said, for performance analysis in A4, further User Interactions are required for creating the 3D representation (models). The division of the A1 module is illustrated in Figure 25. However, this study doesn’t attempt to make any further separation: each sub-module embodies a problem in one discipline.

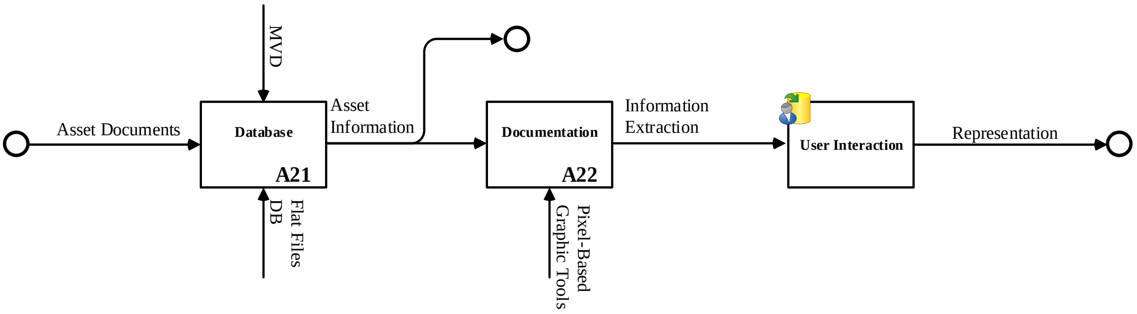


Figure 25 A2 BDS Module (Level 1 Flat Files) Sub-Module Division.

(2) A2 BDS Module (Level 1 Computer-Aided).

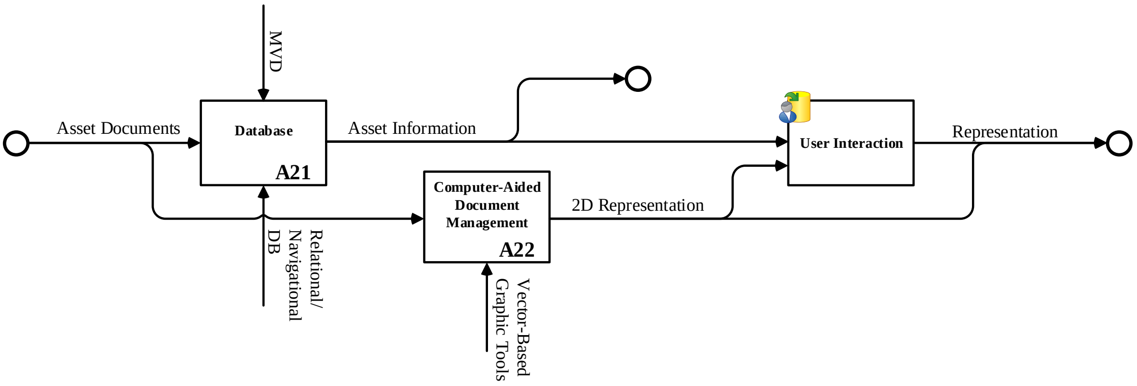


Figure 26 A2 BDS Module (Level 1 Computer-Aided) Sub-module Division.

Decades ago, an evolution of using CAD in building design (A22) carried on. At this level, vector-based graphic tools help improve the drawing accuracy. Therefore, the 2D representation tools are frequently used in building design. However, a range of BPS solutions require 3D representation. This elevated the demand for User Interaction for transforming 2D A22 into 3D models.

In the meantime, at this level, this module adopts a navigational database or relational database (A21). Through a well-defined inner hierarchy, such database is easier for the end user to retrieve information than the flat files database. Furthermore, 2D drafting specification becomes the main specification for Model View Definition (MVD) at this level. On conditions that, the specification is client-proprietary. To put it into another sentence, no commonly standardized MVD can be adopted at this level. The division of the A1 module is illustrated in Figure 26. Based on the functional independence, it is possible to continuingly divide those sub-modules. However, this study doesn't attempt to make any further separation: each sub-module embodies a problem in one discipline.

(3) A2 BDS Module (Level 1 Object-Oriented).

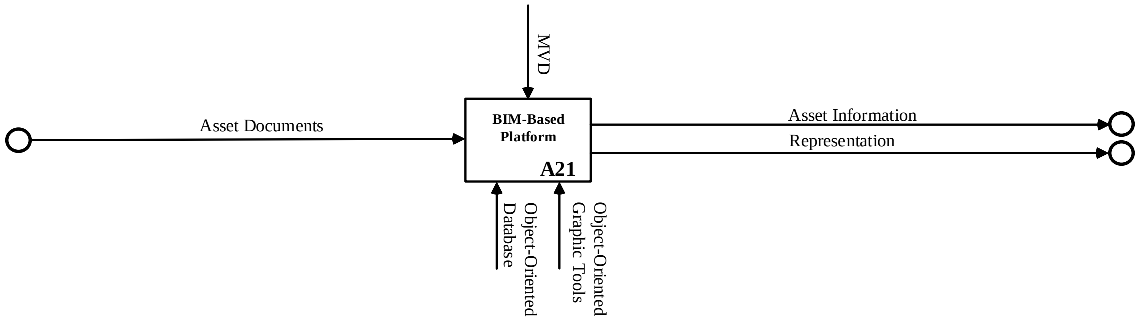


Figure 27 A2 BDS Module (Level 1 Object-Oriented) Sub-Module Division.

BIM-based platforms are centralized in putting A2 to an object-oriented level. This platform has an object-oriented data storage architecture. By using a globally unique identifier (GUID), the end user can store and retrieve elements. The end user can get all information related to an individual element by searching its GUID. Such information includes but is not limited to 1-6D BIM.

Compared with previous generations, this usage level can establish the required multiple-dimensional representations independently. Besides, Construction Operations Building information exchange (COBie), as a standard MVD for construction operations, is used where IFC format is adopted. The division of the A1 module is illustrated in Figure 27. Based on the functional independence, it is possible to continuingly divide those sub-modules. However, this study doesn't attempt to make any further separation: each sub-module embodies a problem in one discipline.

7.2.3 Knowledge-Based System (KBS) Module

In order to retrieve similar cases in case of failure, a framework is established for reasoning. The proposed module can retrieve similar cases for the end user. There are two optional rules in the industry: case-based and rule-based. By using different rules, the KBS can have different sustainable performance.

(1) A3 KBS Module (Option 1 Case-Based).

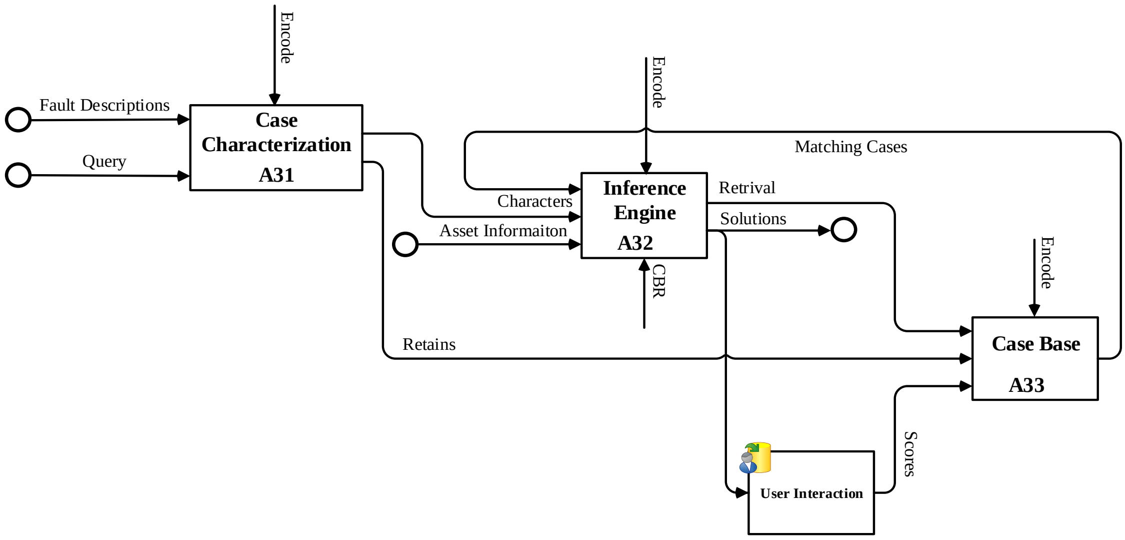


Figure 28 A3 KBS Module (Level 1 Case-Based) sub-module division.

CBR is used to learn from past experiences and seek solutions for a new problem. Before reasoning, the discription of faults will be characterized in A31. Commonly, two components are deployed: the case base (A33) and the inference engine (A32). A32 can retrieve, reuse, revise and retain cases directly from or to A33. A33 is easy to be maintained by the end user because the case is stored in a flat way and retrieved by its characters.

For this purpose, a user-profile score is commonly utilized for maintaining the A33. It is worth noting that built environment classification standards should be adopted. Using standard classification systems can largely build up the efficiency of retrieving. The division of the A1 module is illustrated in Figure 28. All parts within these sub-modules interact mutually inside. This makes the sub-module not independent inside: it can not be divided further.

(2) A3 KBS Module (Option 2 Rule-Based).

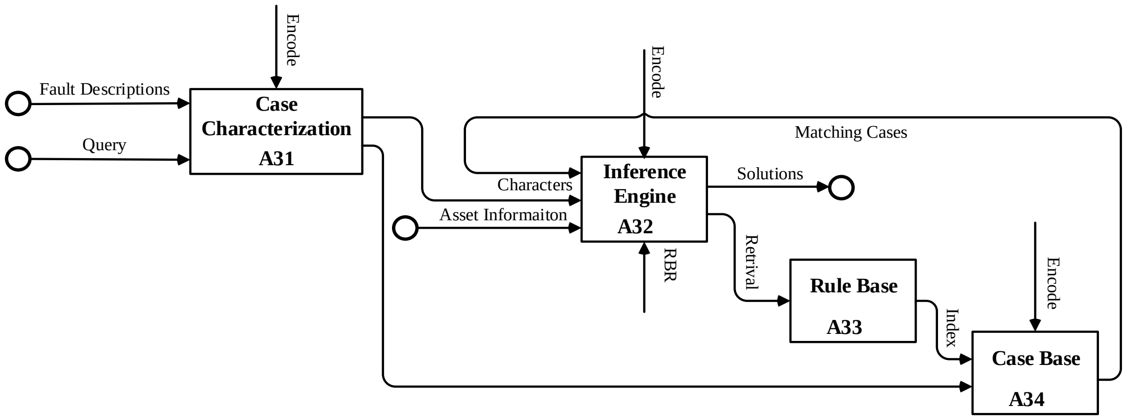


Figure 29 A3 KBS Module (Level 1 Rule-Based) Sub-Module Division.

On the other hand, the RBR method is widely used in industrial fields. Compared with the case-based A3, the rule-based one becomes more automatic. It maintains an explicit model established in A33. Additionally, A34 is indexed by rules. Despite, the end user can barely maintain A34 as they must keep on revising the rules. The division of the A1 module is illustrated in Figure 29. All parts within these sub-modules interact mutually inside. This makes the sub-module not independent inside: it cannot be divided further.

7.2.4 Building Performance Simulation (BPS) Module

A performance simulation is carried out for the A1 under the supervision control. The proposed module can provide energy use simulation results for the end user. As such a framework evolves, there are two use levels in the industry. Using level 2 BPS will reduce the hardware loads than level 1 BPS.

(1) A4 BPS Module (Level 1 Stand-Alone).

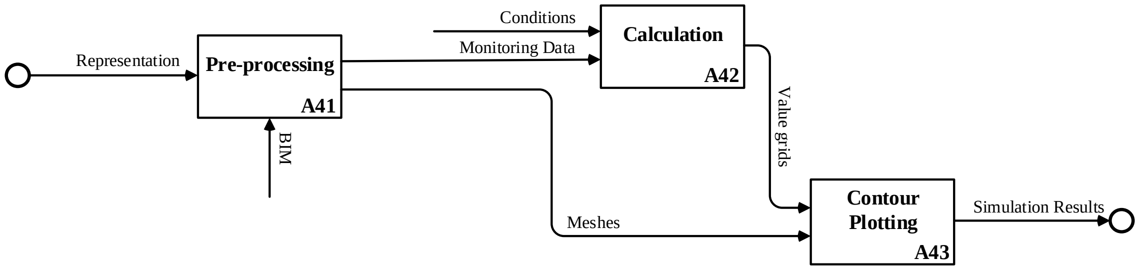


Figure 30 A4 BPS Module (Level 1 Stand-Alone) Sub-Module Division.

Before the simulation starts, the inputs are preprocessed. Some inputs are BIM models, while the others are additional information created manually by the end user. Traditional BPS applications are installed only on PCs. The A42 performance is limited by hardware configuration. To assess building performance in New Zealand, Green Star is adopted. The proposed module enhances the Green Star certification process by standardizing the evaluation process in A4. Consequently, the value grid or list is attained in A43. During contour drawing, the proposed module converts the value to an RGB value. Such RGB value is then rendered to the mesh received from A41. The results are sent to the end user. The division of the A1 module is illustrated in Figure 30. Based on the functional independence, it is possible to continuingly divide those sub-modules. However, this study doesn't attempt to make any further separation: each sub-module embodies a problem in one discipline.

(2) A4 BPS Module (Level 2 Cloud-Based).

In this module, computing processes are put into the cloud for more efficient use of hardware. The end user will send qualified digital representation to A42 and receive similation results in a little while. This becomes a pre-condition for real-time dynamic simulation. The level 1 A4 merely works on stand alone processing. Particularly, at this level, Functional Mock-Up Interfaces (FMI) is adopted to standardize the simulation. FMI is "a tool independent standard to support both model exchange and co-simulation of dynamic models" (Blochwitz et al., 2012). The division of the A1 module is illustrated in Figure 31. Based on the functional independence, it is possible to continuingly divide those sub-modules. However, this study doesn't attempt to make any further separation: each sub-module embodies a problem in one discipline.

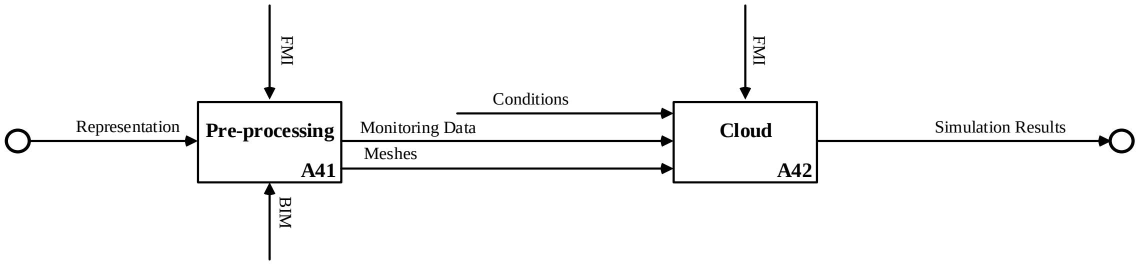


Figure 31 A4 BPS Module (Level 1 Cloud-Based) Sub-Module Division.

7.2.5 Fault Detection and Isolation (FDI) Module

For detecting operational faults, this module carries out FDI. This process detects the failure from the condition monitoring data and outputs the failure to the A3. There are two use levels of FDI in the industrial field. The fault response time varies among various BPS use levels

(1) A5 FDI Module (Level 1 Process History-Based).

The A5 is designed to locate operational faults and send corresponding information to end user. Among the use methods, the most popular one was process history-based. In this use method, the Correlation Indices (CIs) is outputed. Featuring those CIs, algorithms (e.g. QTA, PCA, PPCA, PLS) are characteristically used for unusual signal recognition. When a failure detected, the Reconstruction-Based Contributions (RBCs) are sent to A53. By processing these RBCs, it is expected that A53 will obtain the fault classification coupled with its description. For this purpose, Neutral Networks and Statistic Classifiers can be used. At the same time, it is more effective to use an expert system for fault diagnosis. As mentioned above, an expert system is already designed in A3. To keep A5 functionally independent, such expert system functions are assigned to

A3. The division of the A1 module is illustrated in Figure 32. Based on the functional independence, it is possible to continuingly divide those sub-modules. However, this study doesn't attempt to make any further separation: each sub-module embodies a problem in one discipline.

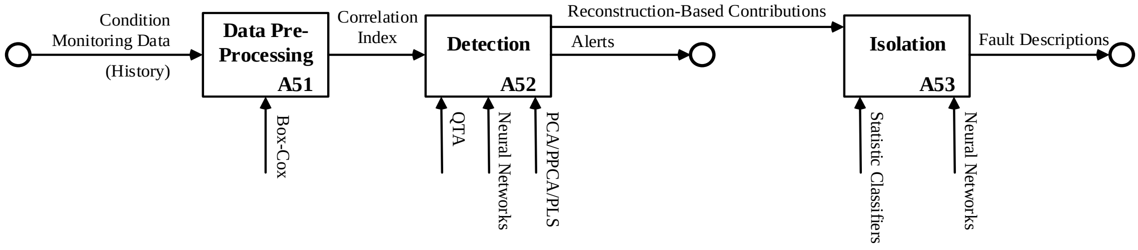


Figure 32 A5 FDI Module (Level 1 Process History-Based) Sub-Module Division.

(2) A5 FDI Module (Level 2 Real-Time).

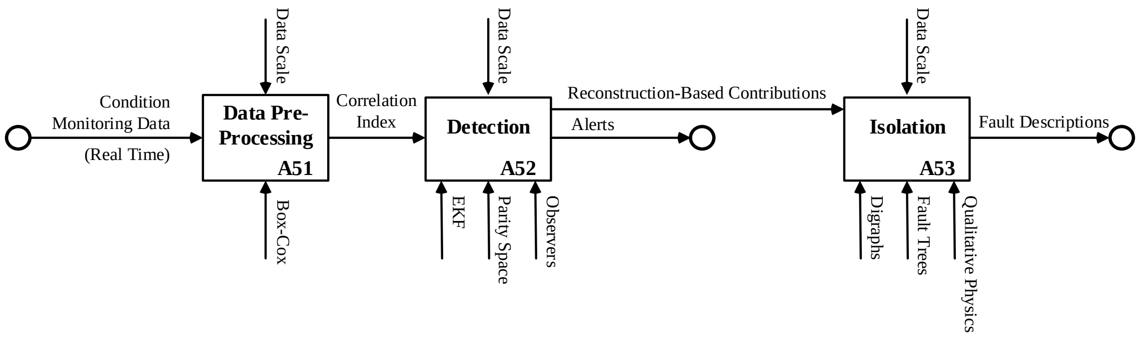


Figure 33 A5 FDI Module (Level 2 Real-Time) Sub-Module Division.

At the first level, the fault response time can hardly be controled. Because the historical process data should be available before the detection and diagnosis. In view of this, a more responsive A5 module is designed. Instead of waiting to collect historical data, such FDI level can process real-time condition monitoring data. With the help of algorithms (e.g. EKF, Parity Space, and Observers), A52 transforms these CIs into RBCs. Fault diagnosis algorithms includes directed graphs, fault trees, and qualitative physics. This FDI level is more sensitive to operational faults. Despite, the data scale often overloads the hardware which processes it in real time. However, due to data noise, insufficient data sets may cause result interference.

The division of the A1 module is illustrated in Figure 33. However, this study doesn’t attempt to make any further separation: each sub-module embodies a problem in one discipline.

7.3 System Interoperability

To improve the interoperativity, the data format diversity and protocol diversity are main barriers. With multiple formats, the proposed system must make the transition from one platform to another. Similarly, it is complex to implement the proposed system that the end user operates devices by using different communication protocols. In addition, sub-modules are evolving itself. That said, it is important to update a sub-module with the minimal influence on the others.

Numerous naming convention systems exist in the AEC/FM industry. This can cause controversy. Particularly, if one organization is tryings to retrieve information from documents issued by another. When the end user learns from past cases, problems will occur if the knowledge is formed in another name convention system. Considering this, standardizing is a nice choice for improving interoperability in the proposed framework.

7.3.1 Standard Communication Protocols

One of the main problems in the early embedded system research is the diversity of communication protocols. It also becomes one of the main challenges for system integration (West & Dedrick, 2011). Proprietary protocols are used by conventional BASs from SCADA level 1 to level 3. Those protocols are developed and used by various vendors. Those protocols largely improve the complexity in multi-vendor systems. Compared with this, standard protocols are more “open”. At SCADA level 4, vendors’ devices are in line with standard protocols. Such open protocols are adopted by the wider industry. The interoperability will be largely improved if all appliances adopt one standard protocol. Representative IoT-oriented protocols include MQTT, and CoAP.

Both two protocols are machine-to-machine (M2M)/IoT connectivity protocols. MQTT is designed as a tremendously lightweight publish/subscribe messaging transport. It is an effective method for connections between remote locations with low/unreliable bandwidth or limited processor/memory resources. While, CoAP is used for communicating in a low-powered and lossy networked environment. Hence, using a standard communication protocol can reduce the complexity of either adding or removing an additional part of the whole system.

7.3.2 Standard Data Formats

Literatures on data exchange in the AEC/FM industry highlights numerous popularly used data formats. Andriamamonjy, Saelens, and Klein (2018) noted that, gbXML is “a flexible, open, straightforward industry supported data schema for sharing building information between disparate building design software tools”. Compared with gbXML, IFC not only focuses on building design and performs a wider extent (C.-S. Park, Lee, Kwon, & Wang, 2013). In order to improve the efficiency after construction, IFC is chosen as the data exchange format.

The IFC 4.0 reference view can be used in almost all the BIM coordination tasks. IFC 4.0 is more sector-specific than IFC 2x4. Furthermore, this standard is ISO certified. Hence, IFC 4.0 was used for data exchange. Despite, incomplete information delivery processes still limit the IFC use. In spite of this, the compatibility issues still occur when the end user uses IFC translators (Venugopal, Eastman, & Teizer, 2015). For meeting the requirement of a discipline, additional information should be added manually (Andriamamonjy et al., 2018). Performance curve is one of the most important features reflecting the different behaviors of components in various situations. In the case of HVAC systems, the performance curves are still missing in IFC4 (Pinheiro et al., 2018). Nevertheless, not all the information is needed when the end user exchanges data.

The requirement for data exchange is various among different purposes. The information required for each exchange is called an MVD. Among those MVDs, COBie concentrates on space and equipment. COBie offers a work sheet of all the building assets. During the design phase, the end user keeps asset information into a standard COBie work sheet. Asset modelling can be typically established in most of the BIM softwares (e.g. Revit). These softwares may follow the MVD in data exchange. Despite this, they still need manually input. This makes the data exchange easily be taken in human errors and omissions (Koo & Shin, 2018). This rises the need for an application with a more specific MVD.

The proposed system can interoperate all modules. Wherein, some IFC types are adopted: IfcPerformanceHistory, IfcPropertySet, IfcPropertySetTemplate, IfcRelAssociateClassification, IfcController, IfcAlarm, IfcEvent, IfcProcudure, IfcTask. The building elements are involved in the IfcDistributionElement. And the real-time condition monitoring data is stored in IfcPerformanceHistory. IfcRelAssociatesClassification covers data point and device address and gateway URL. This IFC type is useful to classify the control elements in the BIM model. Assisted with the classification, the historical monitoring data can be assigned to the matching control elements. However, the BMS protocol is not specified by IFC 4.0. With the purpose of commission and interoperation, it can be mapped to the vendor implementation or the standard protocol.

Adopting BPS level 2, a real-time simulation will be conducted. Numbers of softwares will work together to get the results. At this level, the end user can make simulation data exchange by using a standard FMI. FMI is demonstrated effective in IEA EBC Annex 60 report on interoperating run-time and real time simulation applications (Wetter & Treek, 2017). This report shows a new generation of computational tools for the design and operate of the building/community energy systems. A standard functional interface in simulation will enhance the interoperability of the BPS module.

7.3.3 Standard Naming Conventions

Afsari and Eastman (2016) demostrated the significance of using a standard classification system for defining built environment terms. It is found to be more efficient that the end user organizes building product libraries and classifies building elements in a standard way. Such a standard naming convention, then, benefits the KBS by providing accurate terminologies. There are four most commonly encoders: OmniClass, MasterFormat, UniFormat, and UniClass. UniClass is popularly used in UK, and the others are popular used in a North America context. These encoders are developed based on ISO 12006-2:2015. Despite this, at this time none of them are ISO certified. Without ISO certified, the proposed system can only be used in a specific context. Considering these issues, the prior research has already provided New Zealand specific terminologies. Despite this, a more detailed classification system should be established in New Zealand. In this study, we adopted the terminologies established in Chapter 5 while more detailed naming was carried on by following OmniClass which is already embedded in Revit.

7.3.4 Standard Evaluation Systems

Recently, there are numbers of parameters in a building design that influence the building operational performance. This makes buildings vary from one to another and the operate efficiency can hardly be assessed (Leaman, Stevenson, & Bordass, 2010). For this purpose, it is important to examine the building performance evaluation tools. Through standard evaluation processes, it is expected that the results will be helpful for the end user to make decisions when supervising the operation. For this purpose, numbers of green building standards are developed. Those standards include BREEAM, LEED, CASBEE, Green Star NZ (Doan et al., 2017). Those standards can help the end user to know how sustainable a building is. Considering this, the facility operational performance can be predicted. Despite this, standards vary from different country. With no common use agreement, the proposed system is limited by the context.

7.4 System Flexibility

As disccussed previously, the module in the proposed system is evolving. It is complex to update a part without noticeable effect on the rest. To deliver a highly flexible complex system, it is efficient to follow the independent axiom:

"Maintain the independence of the functional requirements (FRs)."

Suh (2001)

The independent axiom is used to standardize the modulization (A0: A1-5) of the proposed system. By standardizing the process of modulization, the flexibility of the proposed system is largely increased. This flexibility is mainly the capacity of switching out an existing module or adding new modules. In the following paragraghs, a deduction will be carried on. Such deduction will demonstrate how the proposed system satisfy the independent axiom. To verify the functional independence, Design Structure Matrix (DSM) is selected as an examining factor (Kulak, Cebi, & Kahraman, 2010). The Independence Axiom requirements will be satisfied if a DSM can be uncoupled into a coupled matrix or a quasi-coupled matrix (Eppinger; & Browning, 2012).

Table 10 the Divisions of FRs and DPs and Cs.

Factors	Contents	Divisions
FR_0	To provide simulation-based supervisory control while automatically detecting and diagnosing operational faults	FR_1: To provide automatic centralized control of building facilities
		FR_2: To provide a database capable of detailly describing buildings
		FR_3: To solve new problems based on the solutions of similar past cases
		FR_4: To simulate the building performance and provide an optimized scheme for building management
		FR_5: To recognize the operational faults and pinpoint the type of fault and its location
DP_0	ND BIM-IKBMS	DP_1: A1 BAS Module
		DP_2: A2 BDS Module
		DP_3: A3 CBR Module
		DP_4: A4 BPS Module
		DP_5: A5 FDI Module
Cs	Interoperability	C_1: Protocols
		C_2: MVDs
		C_3: Encode
		C_4: Evaluation System
		C_5: Data Scale

This study proposed to obtain a simulation-based supervisory control system. In the mean time, its operational faults can be detected and diagnosed automatically. Towards this end, the FR_0 is divided into five FRs (See in Table 10). Focusing on each FR indivisually, five DPs are established. However, the interactions between two DPs exist. Espectially, one DP is designed to deliver the required functions for its corresponding FR. For example, to satisfy the requirements of the FR_5, DP_5 is created to diagnose the operational faults coupled with their information. In which, DP_5 needs to dispose the conditional monitoring data received from DP_1. Therefore, FR_5-DP_1 interactions exist. A matrix diagram is developed to illustrate the FRs-DPs relationship (See Table 12). In view of this, the FRs-DPs DSM is calculated in Eq. 5 (X: influence; 0: no influence).

Table 11 Mapping between FRs and DPs for ND BIM-IKBMS.

DPs / FRs	**DP₁**	**DP₂**	**DP₃**	**DP₄**	**DP₅**
FR_1	Self-Interaction	Independent Operation	Independent Operation	Independent Operation	Independent Operation
FR_2	Monitoring Data	Self-Interaction	Independent Operation	Independent Operation	Independent Operation
FR_3	Independent Operation	Asset Information	Self-Interaction	Independent Operation	Fault Descriptions
FR_4	Independent Operation	Representation	Independent Operation	Self-Interaction	Independent Operation
FR_5	Condition Monitoring Data	Independent Operation	Independent Operation	Independent Operation	Self-Interaction

$$\begin{vmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \\ FR_5 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 & 0 & 0 \\ X & X & 0 & 0 & 0 \\ 0 & X & X & 0 & X \\ 0 & X & 0 & X & 0 \\ X & 0 & 0 & 0 & X \end{vmatrix} \begin{vmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \end{vmatrix} \quad \text{(Eq. 5)}$$

The DSM is decoupled:

First of all, exchange the FR_3 and FR_4 rows (See Eq. 6).

$$\begin{vmatrix} FR_1 \\ FR_2 \\ FR_4 \\ FR_3 \\ FR_5 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 & 0 & 0 \\ X & X & 0 & 0 & 0 \\ 0 & X & 0 & X & 0 \\ 0 & X & X & 0 & X \\ X & 0 & 0 & 0 & X \end{vmatrix} \begin{vmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \end{vmatrix} \quad \text{(Eq. 6)}$$

Next, exchange the DP_3 and DP_4 column (See Eq. 7).

$$\begin{vmatrix} FR_1 \\ FR_2 \\ FR_4 \\ FR_3 \\ FR_5 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 & 0 & 0 \\ X & X & 0 & 0 & 0 \\ 0 & X & X & 0 & 0 \\ 0 & X & 0 & X & X \\ X & 0 & 0 & 0 & X \end{vmatrix} \begin{vmatrix} DP_1 \\ DP_2 \\ DP_4 \\ DP_3 \\ DP_5 \end{vmatrix} \quad \text{(Eq. 7)}$$

Then, exchange the DP_4 and DP_5 columns (See Eq. 8).

$$\begin{vmatrix} FR_1 \\ FR_2 \\ FR_4 \\ FR_3 \\ FR_5 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 & 0 & 0 \\ X & X & 0 & 0 & 0 \\ 0 & X & 0 & 0 & X \\ 0 & X & X & X & 0 \\ X & 0 & X & 0 & 0 \end{vmatrix} \begin{vmatrix} DP_1 \\ DP_2 \\ DP_4 \\ DP_3 \\ DP_5 \end{vmatrix} \quad \text{(Eq. 8)}$$

Finally, exchange the FR_4 and FR_5 rows (See Eq. 9).

$$\begin{vmatrix} FR_1 \\ FR_2 \\ FR_5 \\ FR_3 \\ FR_4 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 & 0 & 0 \\ X & X & 0 & 0 & 0 \\ X & 0 & X & 0 & 0 \\ 0 & X & X & X & 0 \\ 0 & X & 0 & 0 & X \end{vmatrix} \begin{vmatrix} DP_1 \\ DP_2 \\ DP_4 \\ DP_3 \\ DP_5 \end{vmatrix} \quad \text{(Eq. 9)}$$

It is found that Eq. 9 is a quasi-coupled matrix. This meets the requirements of the Independent Axiom. Therefore, the A0 system is functionally independent.

Furthermore, two pathways are established to satisfy the FR_0.

7.4.1 Simulation-Based Supervisory Control (SBSC)

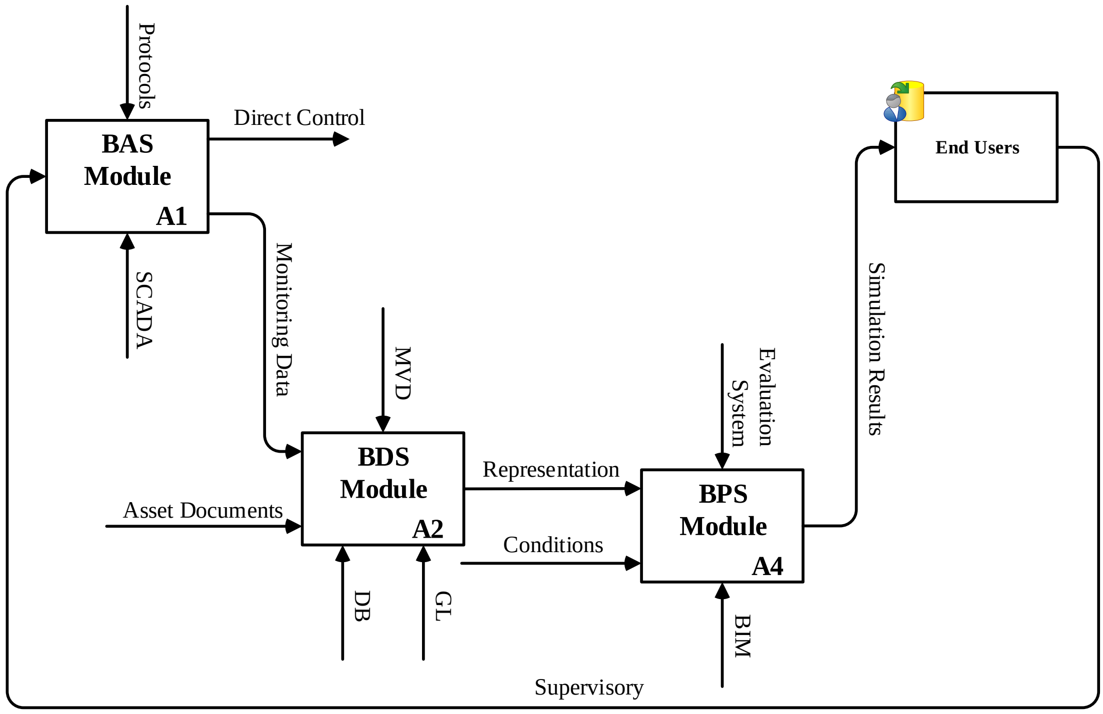


Figure 34 SBSC Pathway Modulization.

The Simulation-Based Supervisory Control (SBSC) pathway proposes to carry on smart supervision control upon the simulated results. In light of this, three modules are used (See in Figure 34). At the very beginning, the A1 monitors the built environment and the end user can import the data to the A2. Paired with the 3D building elements, such monitoring data is imported into A4. This can help the end user to make decisions on operational strategies. Once the simulation done, the results are sent to the end user who is supervising the A1.

Table 12 Mapping between FRs and DPs for SBSC.

FRs \ DPs	DP_1	DP_2	DP_4
FR_1	Self-Interaction	Independent Operation	Independent Operation
FR_2	Monitoring Data	Self-Interaction	Independent Operation
FR_4	Independent Operation	Representation	Self-Interaction

In such pathway, the relationships between FRs and DPs are mapped in Table 12. Considering this, the DSM for mapping FRs and DPs is developed as shown in Eq. 10.

$$\begin{vmatrix} \boldsymbol{FR_1} \\ \boldsymbol{FR_2} \\ \boldsymbol{FR_4} \end{vmatrix} = \begin{vmatrix} \boldsymbol{X} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{X} & \boldsymbol{X} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{X} & \boldsymbol{X} \end{vmatrix} \begin{vmatrix} \boldsymbol{DP_1} \\ \boldsymbol{DP_2} \\ \boldsymbol{DP_4} \end{vmatrix} \text{(Eq. 10)}$$

In result, Eq. 10 is a quasi-coupled matrix. Such matrix satisfies the requirements of the Independent Axiom. Therefore, the SBSC pathway is functionally independent.

7.4.2 Fault-Finding Supervisory Control (FFSC)

The Fault-Finding Supervisory Control (FFSC) pathway proposes to conduct automatic fault detection and isolation. This process is based on simillar solutions from past cases. Considering this, four modules are established (See in Figure 35). At the beginning, the A1 acquisites the condition monitoring data for the facilities. Then, A1 sent the data to A5. After processed in A5, the fault descriptions are sent to A3. In the mean time, asset information (e.g. identification, location) is sent to A3 from A2. The end user is warned with a fault and its location when detected. At the same time, the suggestions from past cases are received. The end user can also quetry manually when there is a need.

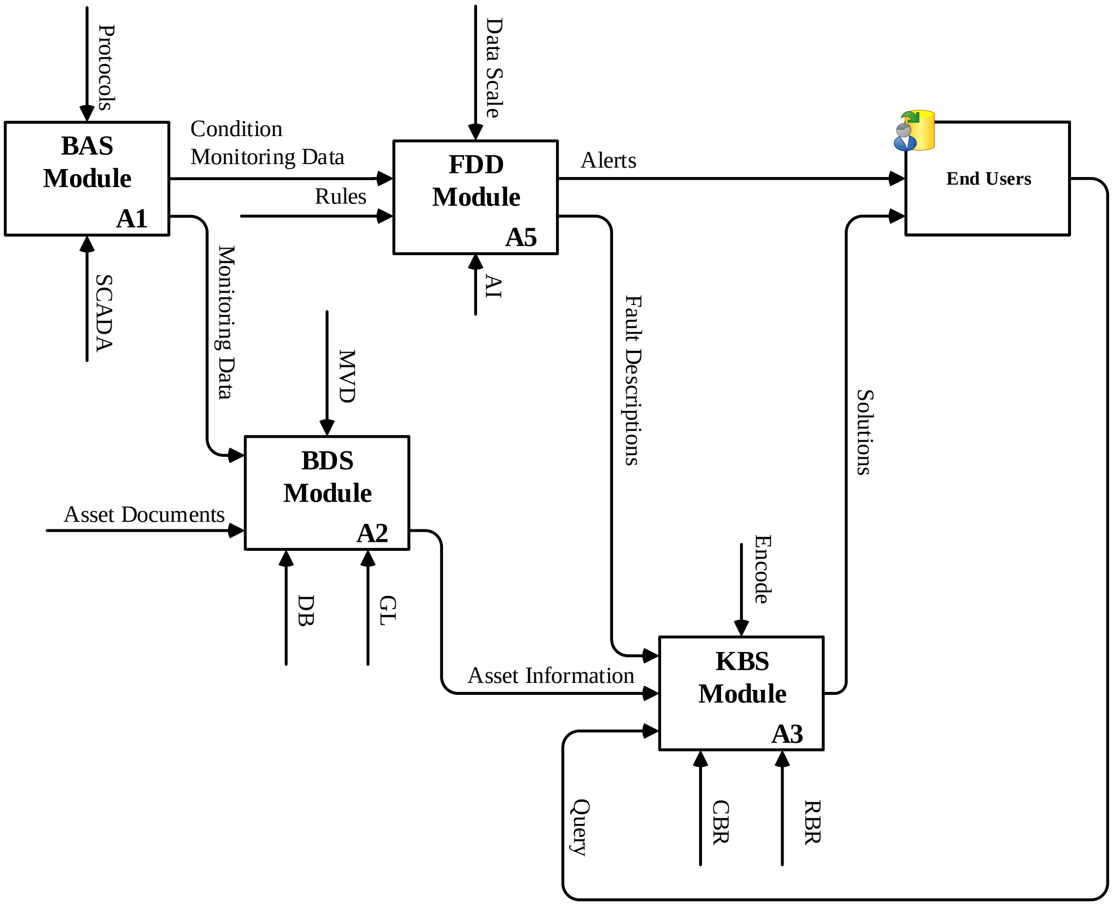


Figure 35 FFSC Pathway Modulization.

Table 13 Mapping between FRs and DPs for FFSC.

FRs \ DPs	**DP₁**	**DP₂**	**DP₃**	**DP₅**
FR_1	Self-Interaction	Independent Operation	Independent Operation	Independent Operation
FR_2	Monitoring Data	Self-Interaction	Independent Operation	Independent Operation
FR_3	Independent Operation	Asset Information	Self-Interaction	Fault Descriptions
FR_5	Condition Monitoring Data	Independent Operation	Independent Operation	Self-Interaction

In this pathway, the FRs-DPs relationships are mapped in Table 13. Considering this, the DSM for mapping FRs-DPs relationships are developed (See Eq. 11).

$$\begin{vmatrix} \boldsymbol{FR_1} \\ \boldsymbol{FR_2} \\ \boldsymbol{FR_3} \\ \boldsymbol{FR_5} \end{vmatrix} = \begin{vmatrix} \boldsymbol{X} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{X} & \boldsymbol{X} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{X} & \boldsymbol{X} & \boldsymbol{X} \\ \boldsymbol{X} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{X} \end{vmatrix} \begin{vmatrix} \boldsymbol{DP_1} \\ \boldsymbol{DP_2} \\ \boldsymbol{DP_3} \\ \boldsymbol{DP_5} \end{vmatrix} \text{(Eq. 11)}$$

First of all, exchange the DP_3 and DP_5 columns (See Eq. 12).

$$\begin{vmatrix} \boldsymbol{FR_1} \\ \boldsymbol{FR_2} \\ \boldsymbol{FR_3} \\ \boldsymbol{FR_5} \end{vmatrix} = \begin{vmatrix} \boldsymbol{X} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{X} & \boldsymbol{X} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{X} & \boldsymbol{X} & \boldsymbol{X} \\ \boldsymbol{X} & \boldsymbol{0} & \boldsymbol{X} & \boldsymbol{0} \end{vmatrix} \begin{vmatrix} \boldsymbol{DP_1} \\ \boldsymbol{DP_2} \\ \boldsymbol{DP_3} \\ \boldsymbol{DP_5} \end{vmatrix} \text{(Eq. 12)}$$

After that, exchange the FR_3 and FR_5 columns (See Eq. 13).

$$\begin{vmatrix} \boldsymbol{FR_1} \\ \boldsymbol{FR_2} \\ \boldsymbol{FR_5} \\ \boldsymbol{FR_3} \end{vmatrix} = \begin{vmatrix} \boldsymbol{X} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{X} & \boldsymbol{X} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{X} & \boldsymbol{0} & \boldsymbol{X} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{X} & \boldsymbol{X} & \boldsymbol{X} \end{vmatrix} \begin{vmatrix} \boldsymbol{DP_1} \\ \boldsymbol{DP_2} \\ \boldsymbol{DP_3} \\ \boldsymbol{DP_5} \end{vmatrix} \text{(Eq. 13)}$$

Consequently, Eq. 13 is a quasi-coupled matrix. This matrix can meet the Independent Axiom requirements. Therefore, the FFSC pathway is functionally independent.

This research divided complex system (A0) into five parts. And each part is customized to be functional independence. Altogether, it is found that through a standard modulization, a new module can update on its old one without noticeable effect on the rest. Hence, it is found that the proposed system remains high interoperability to change.

7.5 Summary

This chapter presents the outcomes of the axiom design. The significance of nD BIM-IKBMS is demonstrated in the above sections. In this study, we have established a conceptual framework the nD BIM-IKBMS. The proposed framework will be adopted for developing a working prototype in the next research. Such a working prototype is found to be capable of improving the post-construction energy conservation and maintenance effectiveness. In the mean time, the proposed framework is a pre-condition for a higher BIM maturity level. Especially, it is essential for organizations to achieve BIM Level 3.0 and further.

The findings answered the investigating questions (Q9-Q12) proposed in this study. First, the overall function of the proposed system is identified as providing simulation-based supervisory control, and automatically detecting and diagnosing operational faults. It is comprised of five modules. The functions for each module have been given in this chapter. Second, towards adopting an integration of BIM and BMS, the SBSC pathway should be adopted towards integrating BIM and BMS, Wherein, BAS Module, BPS Module, BPS Module were needed. Third, the proposed framework will be adopted for developing a working prototype in the next research. Such a working prototype is found to be capable of improving the post-construction energy conservation and maintenance effectiveness. In the mean time, the proposed framework is a pre-condition for a higher BIM maturity level. Especially, it is essential for organizations to achieve BIM Level 3.0 and further. Finally, a knowledge base for the operational faults coupled with solutions are needed in the future development. Such a knowledge base will be used to develop the FFSC pathway.

Chapter 8 Results and Analysis from Agile Development

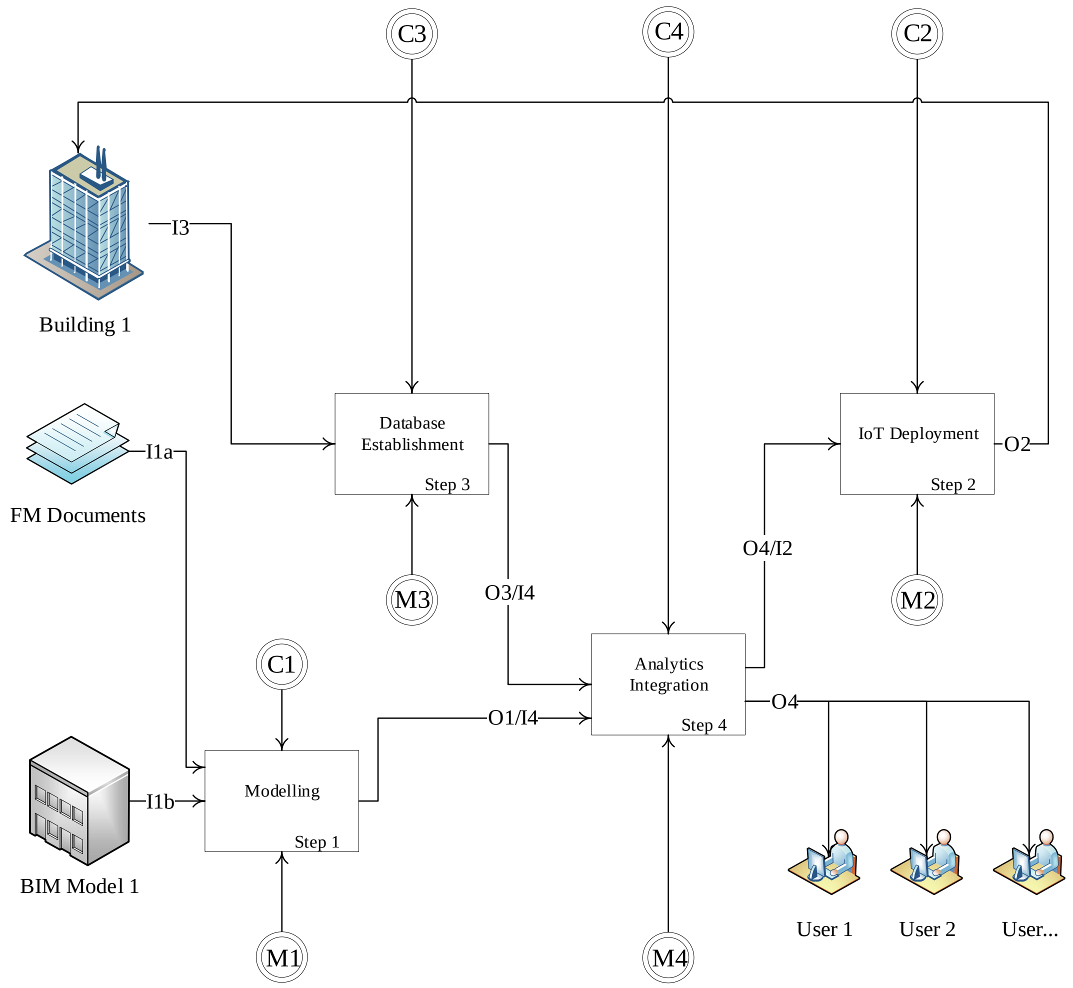
8.1 Introduction

In order to facilitate highly efficient building intelligence, a framework was established by using axiom design. Upon it, an IoT-enabled BIM-based application was developed. To begin this process, Autodesk Revit was used to create the BIM models. Refer to Autdesk Inc. (2018), Revit is a BIM tool which assists the end users to carry out building design in 3D, annotating 2D drafting elements, and retrieving building information from the database. Such BIM models should cover architectural, structural and MEP elements.

Due to the large file size of .rvt generated from Revit and unfriendly UI for non-expert end users, it was proposed to develop a lightweight web platform with a simple UI. For this purpose, WebGL was adopted to visualize 3D models. WebGL is a JavaScript API for rendering interactive 2D and 3D graphics within any compatible web browser without the use of plug-ins (Khronos Group, 2018). Besides, three.js (Javascript 3D library) was used for avoiding repeating works as it has already refined some functions for using WebGL.

To make sure the models can be used in our WebGL-powered User Interface (UI), JavaScript Object Notation (JSON), a lightweight language independent data-interchange format, was adopted as the exchange format. A browser can only exchange data with a server in text format. JSON is a text format, provided that, it is capable of communicating between the browser and serve (W3Schools, 2018). There are some open source Revit Plugins available for this purpose, such as ADN JSON Exporter (Tammik, 2016), etc. Alternatively, we can export .3ds from Revit, and then, use Clara.io to transform .3ds into .json. Clara.io is a web-based freemium 3D computer graphics software developed by Exocortex (Houston, 2013). It is handy when transforming 3D models from one format into another; to prototype the facilities, especially the HVAC system, a master-slave pattern was configured. Raspberry Pi was selected as the master while Arduino was selected as the slave.

The Raspberry Pi is a series of open-source small single-board high performance computers developed by Foundation (2018). In Raspberry Pi, codes were running in a Linux system. Likewise, Arduino is an open-source single-board microcontrollers (Arduino, 2018). Both of Raspberry Pi and Arduino were made for building digital devices and interactive objects that can monitor and control objects in the physical and digital world. Particularly, Raspberry Pi has a mini computer interface operating Linux, provided that, it will be more convenient for it to deploy web-based applications. Hence, Raspberry Pi was operating as a master for the facilities and communicating with the end users by WIFI, while Arduino was connected by cables and actuate as a slave based on the commands received from the master. Once deployed, serial communication was made through sending and receiving Hexadecimal data. To store and analyse the monitoring data, MySQL was used for establishing the database. MySQL is an open-source relational database management system (Corporation, 2018). It is a fast, stable and multi-user, multi-threaded SQL database server. After that, we put the application in the cloud so that all the end users can easily assess it with proper authority. Meanwhile, analysis functions were integrated on the back-end portion of the application. Finally, the proposed system will be applied on a New Zealand building, and the process of data acquisition will be carried on. (See the development process in Figure 36)



(I1a: .pdf FM documents; I1b: .rvt; O4/I2: Hex text; I3: monitoring data; O1/I4: .json; O3/I4: .mysql database; O4: simulation analysis results; O4/I2: Hex text; O2: binary; C1: LOD Specification; M1: C#, .net framework; C2: MQTT protocol; M2: Linux, Python, C; C3: SQL specification; M3: SQL; C4: Cloud server specification; M4: html, javascript, css, php, jquery)

Figure 36 Development Process Model.

8.2 Process Model

8.2.1 User Centred Design

Based on the functional framework, the process model was developed (See Figure 36). Towards obtaining a better understanding of the user requirements, a user-centred design was conducted throughout the development process. Prior to commencing this study, a workshop with the AUT Enterprises Ltd (AUT Ventures) was organized (See Table 14). AUT Enterprises Ltd is the commercialisation arm of AUT. their missions are to develop AUT's commercial capability into a tightly focused, highly effective delivery platform that is sustainable, economically viable and socially responsible. Tech transfer is important for enabling academic research outcomes to meaningfully impact real world settings. Hence, AUT Enterprises Ltd was selected for establishing a kick-start meeting. The potential end users were identified as: architectural designers, construction contractors, building operators.

Table 14 End-User Engagement Workshop 1.

Presenter: Tongrui ZHANG **Date**： 13:00-14:00, 18 October, 2016
Location: AUTEL
Participants: Person 1, PhD, Lecturer, University; Person 2, PhD, Senior Commercialisation Manager, Ventures; Person 3, Intellectual Property & Commercialisation Officer, Ventures.
Outcomes: Presented the concepts of BIM-BMS integration; The potential end users were identified as architectural designers, construction contractors, building operators.

As the construction contractors cooperate mostly with both the designers and the operators, an end-user engagement meeting with a construction company in New Zealand was organized (Table 15). Then, the workshop indicated that the building construction contractors might not be the potential end-users while the building operators were. At the meeting with a building design company, the designers also supported this point of view (See Table 17). Despite this, the engagement of construction contractors in implementing such a system was still a need. As discussed in the focus group interview, it will be more difficult for the FM people to use the proposed system without the early preparation for satisfied BIM models by the designers and construction contractors. In light of this, we organized a workshop with an FM team for an educational building (See Table 16). As a result, the FM team confirmed that they were the right end users of the proposed system while agree on applying the proposed system on one of their buildings. During this time, several demos were made for presenting the proposed system (See Figure 37).

Table 15 End-User Engagement Workshop 2.

Presenter: Tongrui ZHANG **Date**：14:00-15:00, 14 December, 2016

Location: Building Contractor

Participants:

Person 4, Senior Commercialisation Manager, Ventures;

Person 5, PhD, Innovation Strategy Analyst, Group Innovation, Building Contractor.

Outcomes:

Presented the concept of BIM-BMS integration;

Identified the significance of BIM in the AEC industry;

Identified that the potential customers would be the building owners or property management teams.

Table 16 End-User Engagement Workshop 3.

Presenter: Tongrui ZHANG **Date**：13:00-15:00, 15 June, 2017

Location: Educational Estates Group

Participants:

Person 6, PhD, Lecturer, University;

Person 7, PhD, Post-doctoral Research Fellow, University;

Person 8, PhD, Senior Commercialisation Manager, Ventures;

Person 9, Intellectual Property & Commercialisation Officer, Ventures;

Person 10, Director of Facilities Services (FM), Educational Estates Group;

Person 11, Associate Director of Facilities Operations (FM), Educational Estates Group;

Person 12, Associate Director of Facilities Operations (FM), Educational Estates Group;

Person 13, Maintenance Manager (Electrical), Educational Estates Group;

Person 14, Maintenance Manager (HVAC), Educational Estates Group;

Person 15, Maintenance Manager (Building Services), Educational Estates Group;

Person 16, FM Transformation Project Manager, Educational Estates Group.

Outcomes:

Presented the idea of BIM-BMS integration with a short demo video;

Identified the shortcomings of current building facility O&M in educational buildings;

Identified the potential uses of BIM-BMS in educational facility O&M;

Agreed on applying BIM-BMS system on Educational Building A.

Table 17 End-User Engagement Workshop 4.

Presenter: Tongrui ZHANG **Date**：11:00-12:00, 14 August, 2017

Location: Architectural Design Company

Participants:

Person 17, PhD, Lecturer, University;

Person 18, PhD, Senior Commercialisation Manager, Ventures;

Person 19, National BIM Manager - Senior Associate, Architectural Design Company;

Person 20, Digital Innovation Lead - Senior Associate, Architectural Design Company;

Person 21, Architect, Architectural Design Company.

Outcomes:

Presented the idea of BIM-BMS integration with a short demo execution file for the selected building;

Identified the significance of integrating BIM and BMS;

Received positive comments for the idea of the integration of BIM and BMS;

Obtained some suggestions on developing a Revit plugin, solving issues on the construction handover;

Agreed that the industry is currently missing validation of BIM;

Identified that the potential users should be the building owners or operators.

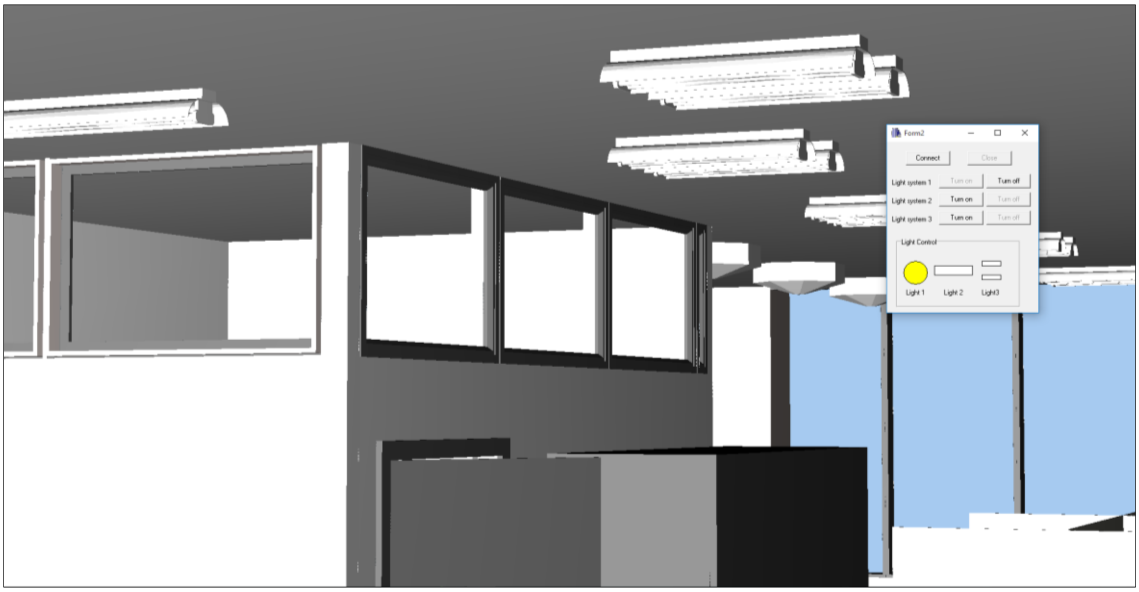


Figure 37 a Demo for the Proposed System.

After that, a focus group mentioned was organized to get the user-centered information on the side time. Five interviewees were recruited from New Zealand architecture, engineering and construction and facilities management (AEC/FM) industry. During the focus group interview, one interviewee can respond to what others have said at any time. They are able to give the opposite points of view once disagreeing. The biases are largely reduced, on conditions that, they are from different companies. Subsequently, they may agree on one point. Otherwise, the disputes will be reported, so that, the inconsistency in the industry will be further analyzed. The interviewees identified the barriers in New Zealand for proposing BIM in FM paired with several suggestions for solving such problems. In a result of this, they remarked that the BIM adoption in New Zealand shown in the literature was true and stable while hard to change. Provided that, there were few flagship projects claimed to adopt BIM without validation for the extent of BIM use and benefits.

Interestingly, most of the interviewees felt that due to the current BIM readiness in New Zealand organizations, there are no benefits for going the extra mile (and cost) to operate and maintain a fully integrated BIM model. On the other hand, the findings identified that there is a trend of abuse BMS in New Zealand. The interviewees agreed that current BMSs in New Zealand were not intelligent enough.

They confirmed the weakness of BMS identified in the literature: big and fragmented data. Meanwhile, they also noted that keeping BMS up-to-date is time- and cost-consuming. Despite this, they still believed that with a mature organizational readiness, proposing BIM can largely facilitate the intelligence of BMS, which will pass the effect to the building performance. In view of BIM, the interviewees suggested promoting building intelligence beyond BMS. One of the interviewees from a BMS provider suggested that the first step of the integration should focus on HVAC. He stated that around 80% of BMSs in New Zealand were managing HVAC because it is not only the biggest cost driver for the operation but also the biggest comfort driver for occupancy.

When asked about managing HVAC systems in New Zealand, the participants were unanimous in the view that current HVAC systems were lack of performance analysis. Those systems were usually heating and cooling at the same time. The interviewees suggested that the future of building performance analysis will be the engagement of AI.

Another key aspect to remember, the participants suggest involving BMS dashboard into BIM. They remarked that the proposed BMS should be capable of setting thresholds and alerting, integrating FM documents, and providing a monitoring database. Particularly, an IoT system was suggested by the participants to adopt for replacing the traditional BMS. Essentially, how to maintain the proposed system up-to-date was identified in the interview as a problem that might not be solved at this time. All things considered, the main objective of this research was established: to develop a BIM-enabled IoT-based application towards highly efficient building intelligence, which includes: (1) to develop a 3D visualized UI for presenting the BIM models; (2) to deploy an HVAC prototype for smart control and monitoring; (3) to integrate BIM visualized UI with facilities; and (4) to embed an analysis application for HVAC performance.

8.2.2 Modeling Process

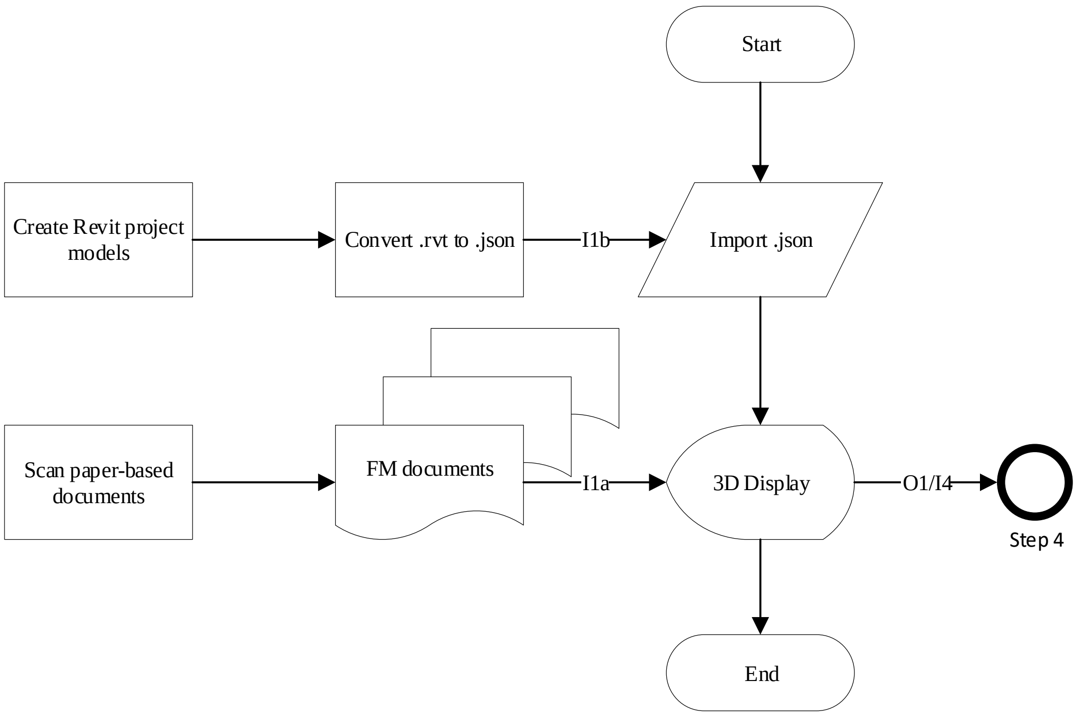


Figure 38 the Modeling Process.

To develop a 3D visualized UI, the first step in this process was to carry on the modeling. As discussed above, a JSON file should be obtained in order to visualize 3D entities in the browser (See Figure 38). Yet, the most popular used BIM file format is .rvt. There is a need to make a transformation for the BIM models from .rvt to .json. Tammik (2016) noticed that a framework for developing a Revit plugin for exporting JSON was given. C# Language and the .NET Framework was adopted. Prior to implementing the execution, a definition of the JSON format was required to be defined. With this in mind, AdnMeshData class was defined to specify the data format as followings:

```
public class AdnMeshData{
 public AdnMeshData(){}
 public int FacetCount{get; protected set;}
 public int VertexCount{get; protected set;}
 public double[] VertexCoords{get; protected set;}
 public int[] VertexIndices{get; protected set;}
 public double[] Normals{get; protected set;}
 public int[] NormalIndices{get;protected set;}
 public double[] Center{get; protected set;}
 public int[] Color{get; protected set;}
 public string Id{get;protected set;}
 }
```

Once the JSON format was assembled, a member function of AdnMeshData was given to generate JSON files, named ToJson(). As the results of the export process, the generated JSON file contains all the necessary geometry information, which is capable of passing on to the browser for 3D reconstruction.

```
public string ToJson(){

  string s = string.Format( "\n \"FacetCount\":{0}," + "\n \"VertexCount\":{1}," + "\n
\"VertexCoords\":[{2}]," + "\n \"VertexIndices\":[[34]]," + "\n \"Normals\":[{4}]," + "\n
\"NormalIndices\":[{5}]," + "\n \"Center\":[{6}]," + "\n \"Color\":[{7}]," + "\n \"Id\":\"{8}\"",
FacetCount, VertexCount, string.Join( ",", VertexCoords.Select<int, string>( i => ( _export_factor * i
).ToString( "0.#" ) ).ToArray() ),string.Join( ",", VertexIndices.Select< int, string >( i => i.ToString()
).ToArray() ), string.Join( ",", Normals.Select<double, string>( a => a.ToString( "0.####" ) ).ToArray() ),
string.Join( ",", NormalIndices.Select<int, string>( i => i.ToString() ) ), string.Join( ",",
Center.Select<int, string>( i => ( _export_factor * i ).ToString( "0.#" ) ) ), Color,Id );

  return "\n{" + s + "\n}";

}
```

Then, the paper-based FM documents were scanned into PDF format and they were embedded into each corresponding element by using the following JQuery functions:

```
document.addEventListener("click", function(){

$(document).ready(function(){

$( "#DocumentName" ).dialog({ maxWidth:Number,maxHeight: Number,width: Number,height:
Number, autoOpen: true );

});
```

Meanwhile, all the PDF should be uploaded to the backend repository. While in the index HTML file, a div should be created for presenting those PDF documents, as followings:

```
<div id="DivID" title="Title">

<iframe height="Number" width= "Number" src="http://FileDirectory.pdf"></iframe></div>
```

As discussed above, we have created a JSON file for containing the 3D geometry information extracted from the RVT file; integrated the FM documents to their corresponding elements. Despite this, the facility monitoring and control functions haven’t been embedded into the related entities.

8.2.3 IoT Process

Having discussed how to conduct modeling, this section addresses ways of deploying IoT. There are numbers of communication protocols including master-slave, client-server, peer to peer, and other modes. To begin this process, a master-slave configuration was adopted (See Figure 39).

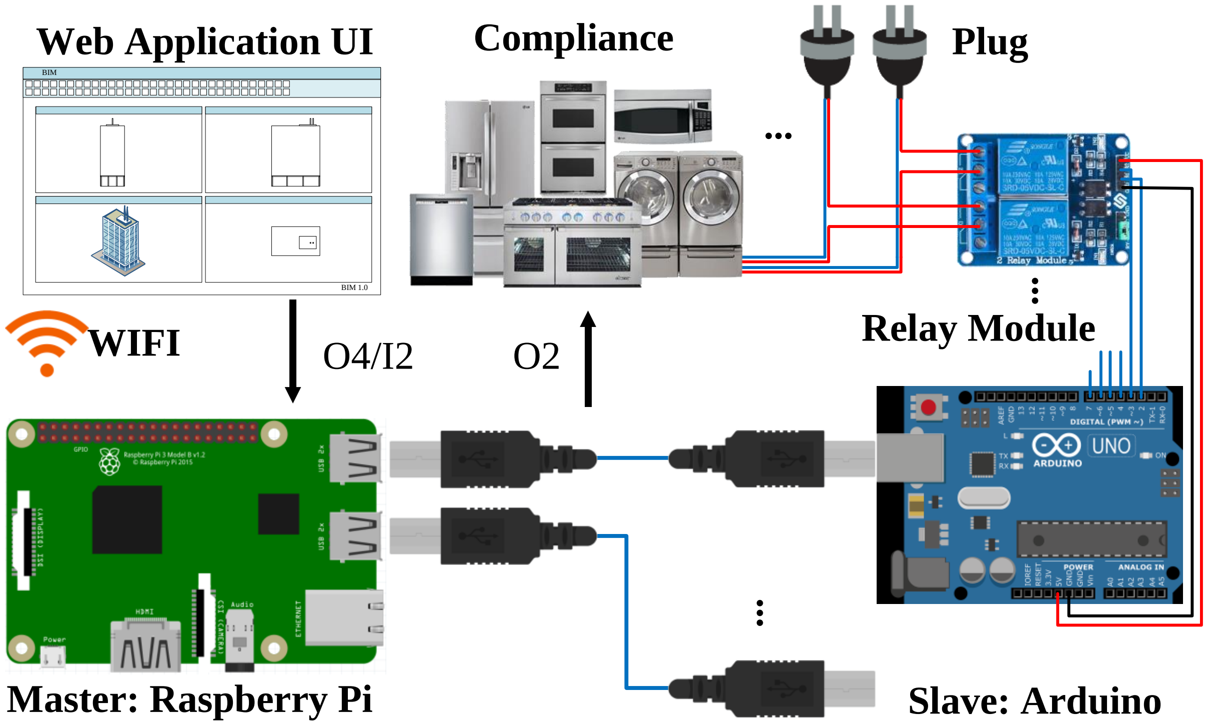


Figure 39 the IoT Control Schema.

That was because our proposed system preserves a web-based UI for managing building facilities. Likewise, a unique master node is connected to several slave nodes and has unidirectional control over them (Boyd, 2011). Operating in Linux, Raspberry Pi was used as the master. It was connected with the end users through the browser while controlled its slaves by sending commands. Unlike the master, slaves focus on taking actions based on the commands received. (See the hardware deployment for this research in Figure 40).

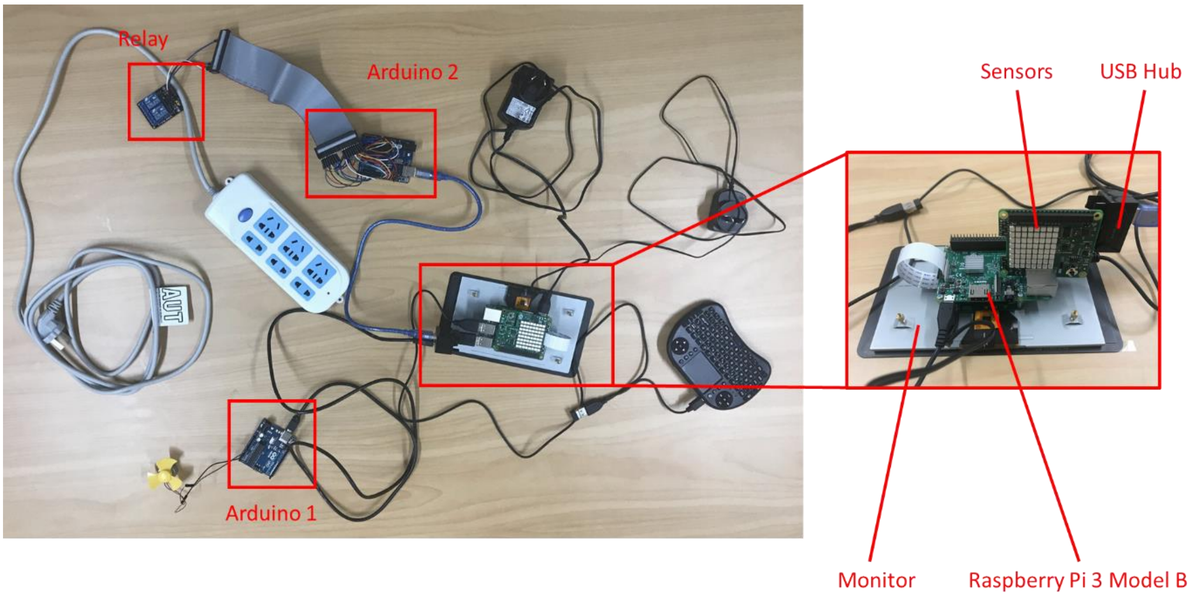


Figure 40 the Hardware Deployment (the New Zealand Building).

Relay modules were deployed for controlling the compliance digitally by using digitalWrite(pin,value). While the analogical control was also achievable by analogWrite(pin, value) an analog value (PWM wave) to a pin. The sample codes:

```
void setup() {
pinMode(PinNumber, OUTPUT);
digitalWrite(PinNumber, HIGH);
}
void loop() {
digitalWrite(PinNumber, LOW);
delay(3000);
digitalWrite(PinNumber, HIGH);
delay(3000);
}
```

To conduct monitoring, variable sensors were connected to either Arduino or Raspberry Pi. Then, the monitoring data was read by analogRead(pin).

```
void setup() {Serial.begin(9600);}
void loop() {
int sensorValue = analogRead(PinNumber);
Serial.println(sensorValue);
delay(1);
}
```

As a result, the functions for monitoring and control have been presented in Figure 41. Having said that, the monitoring data was not stored in the database at this stage. This will be addressed in the next section.

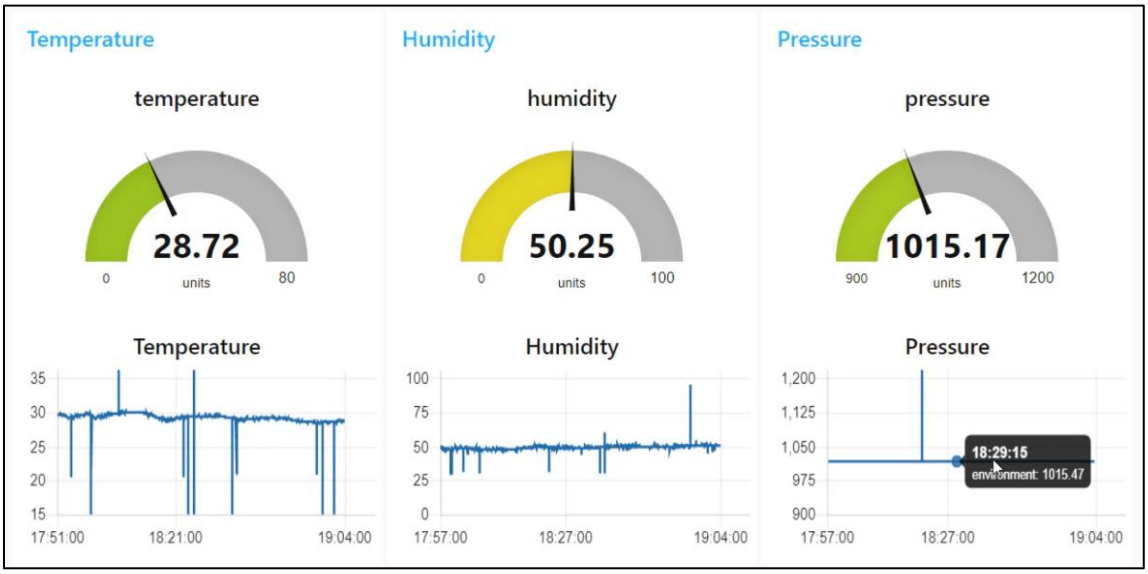


Figure 41 the UI for Monitoring and Control (the New Zealand Building)

When deploying the Raspberry Pi, Nodered.js was used for simplifying the dashboarding process. The master in this research should be capable of communicating with its slaves. The development of management functions for the master can be made in Nodered.js with the codes below:

{"id":"","type":"serialout","z":"","name":"HVAC_Number","serial":"","x":,"y":,"wires":[]},

{"id":"","type":"ui_button","z":"","name":"","group":"","order":0,"width":0,"height":0,"passthru":false,"label":"HVAC_ON","color":"","bgcolor":"","icon":"","payload":"Command_ON","payloadType":"str","topic":"","x":,"y":,"wires":[[""]]},

{"id":"","type":"ui_button","z":"","name":"","group":"","order":0,"width":0,"height":0,"passthru":false,"label":"HVAC_OFF","color":"","bgcolor":"","icon":"","payload":"Command_ON","payloadType":"str","topic":"","x":,"y":,"wires":[[""]]},

{"id":"","type":"serialport","z":"","serialport":"/dev/ttyACM0","serialbaud":"9600","databits":"8","parity":"none","stopbits":"1","newline":"\\n","bin":"false","out":"char","addchar":false}

Two buttons were created in the dashboard. When clicking “HVAC_ON”, it will send a message to its slaves, which is defined in “Command_ON”. Such a message can be an English alphabet, for instance, “o”. Before operating, the ASCII code for “o” (111) should also be set in the slaves coupled with several actions such as digitalWrite(). Once Serial.read() equal to the pre-defined ASCII value, the actions will be taken. Example codes have been given as follows:

```
#define HVAC_ON PinNumber
int Command = 0 ;
void setup()
{
 Serial.begin(9600);
 pinMode(HVAC_ON,OUTPUT);
}
void loop()
{
 if(Serial.available()>0)
 {
  temp=Serial.read();
  switch (command){
  case (ASCII_code) :
   {
   digitalWrite(HVAC_ON, HIGH);
   break;
}}}}
```

8.2.4 Database Process

In order to store the monitoring data for further use, a relational database was adopted. According to Maier (1983), a relational database contains multiple tables of data that relate to each other through special key fields. Compared to the flat file database which contains a single table of data, a relational database was expected to be far more flexible. As mentioned before, MySQL is a typical tool capable of configuring such a relational database. With the help of nodered.js, a MySQL database was then created and connected.

{"id":"","type":"mysql","z":"","mydb":"","name":"DatabaseName","x":,"y":,"wires":[[""]]},
{"id":"","type":"MySQLdatabase","z":"","host":"127.0.0.1","port":"3306","db":"TableName","tz":""}

Therein, a table was created to store three streams of data from the sensors: temperature, humidity, and pressure. The data type was pre-set as followings:

{"id":"","type":"inject","z":"","name":"create db table","topic":"CREATE TABLE TableName(
TIMESTAMP bigINT NOT NULL PRIMARY KEY , temperature float NOT NULL, pressure float NOT NULL,
humidity float NOT NULL)","payload":"","payloadType":
"date","repeat":"","crontab":"","once":false,"x":,"y":,"wires":[[""]]}

To unify the data format between analogRead() and the table in MySQL database, the following transformation was made:

{"id":"","type":"change","z":"","name":"Remove single quotes","rules":[{"t":
"change","p":"payload","pt":"msg","from":"'","fromt":"str","to":"","tot":"str"}],"action":"","property
":"","from":"","to":"","reg":false,"x":,"y":,"wires":[[""]]}

Then, in order to create a SQL query for a database, a "write query" function should be defined as below:

{"id":"","type":"function","z":"","name":"write query","func":"var timeStamp = msg.payload.E; \nvar
pressure=msg.payload.P; \nvar temperature=msg.payload.T;\nvar humidity=msg.payload.H;\nvar
newMsg = { payload: msg.payload };\n\nvar insertString=\"INSERT INTO TableName VALUES (\"
+\ntimeStamp + \", \" +\ntemperature + \", \"+ \npressure + \", \" +\nhumidity +
\")\";\nnewMsg.topic=insertString;\nreturn newMsg;","outputs":1,"noerr":0,"x":,"y":,"wires":[[""]]}

Last, the SQL "select" statement was used to return a result set of records for the table just created.

{"id":"","type":"inject","z":"","name":"","topic":"select * from TableName WHERE TIMESTAMP >= UNIX_TIMESTAMP('Date_1 Time_1') and TIMESTAMP<=UNIX_TIMESTAMP('Date_2 Time_2')","payload":"","payloadType":"date","repeat":"","crontab":"","once":false,"x":,"y":,"wires":[[""]]}

Thus far, a MySQL database was configured for the proposed system while relational tables were created. This can be used for either historical retrieval or performance prediction and simulation which will be presented in the next section.

8.2.5 Simulation Process

The previous discussion has shown how building facility smart management can be achieved. To facilitate the building intelligence beyond such smart management, this research intends to promote the engagement of analysis. In light of this, the application was put into the cloud while integrating the analysis functions on the back-end portion of the application.

Figure 42 3D Import by three.js (the New Zealand Building).

Once obtained JSON files from the modeling stage, three.js was used to load the geometry and create the scene. Three.js is a WebGL-based cross-browser JavaScript library, and Application Programming Interface (API) used to create and display animated 3D computer graphics in a web browser (mrdoob, 2018). The codes for loading JSON by using three.js was given as below:

```
var objectLoader = new THREE.ObjectLoader();

objectLoader.load("ModelName.json",function (obj) {scene.add(obj);});
```

After rendering in WebGL engine, the model was successfully imported as shown in Figure 42. To manage the geometry in an object-oriented way, a "picking" function was made based on the element name or ID. With this in mind, a "click" event listener was added into the proposed system. It detected the mouse click and returned the coordinates of the position clicked.

```
window.addEventListener('click', function(event){

event.preventDefault();

mouse.x =  (event.clientX /window.innerWidth ) * 2 - 1;

mouse.y = -(event.clientY/window.innerHeight ) * 2 + 1;

raycaster.setFromCamera( mouse, camera );

var intersects = raycaster.intersectObjects(scene.children, true);

if( intersects.length>0 ){if( INTERSECTED !=intersects[ 0 ].object ){if( INTERSECTED
){INTERSECTED.material.emissive.setHex( INTERSECTED.currentHex );INTERSECTED=intersects[ 0
].object;INTERSECTED.currentHex=INTERSECTED.material.emissive.getHex();INTERSECTED.material.e
missive.setHex(0x3399ff
);}if(INTERSECTED.name=="ElementName"){$(document).ready(function(){$( "#MasterName"
).dialog({ maxWidth:Size,maxHeight: Size,width:Size,height:Size,autoOpen:true });});}}}

else{if( INTERSECTED )INTERSECTED.material.emissive.setHex( INTERSECTED.currentHex
);INTERSECTED = null;}

},false)
```

Meanwhile, a “Raycaster” was used for generating a project that renders a 3D world based on a 2D map. By calculating the intersection of the click position and the raycaster, the intersected element was expected to be identified. The “Raycaster” function was given as below:

```
function Raycaster( origin, direction, near, far ) {
this.ray = new Ray( origin, direction );
this.near = near || 0;
this.far = far || Infinity;
this.params = {Mesh: {},Line: [12], LOD: [12], Points: [12], Sprite: [12]};
Object.defineProperties( this.params,{PointCloud:{get:function(){console.warn( 'THREE.Raycaster: params.PointCloud has been renamed to params.Points.' );return this.Points;}}});
}
```

To embed the IoT dashboard developed in the previous section, jQuery was used to make pop-up forms. For this purpose, the following codes were inserted into the “Click” event listener above and popped forms when the corresponding element was detected to be picked.

```
function(){
$(document).ready(function(){
$("#MasterName").dialog({ maxWidth: Size,maxHeight:Size,width:Size,height:Size,autoOpen: true });
});
```

In addition, the IoT dashboard was embedded into the HTML files by using “iframe”.

```
<div id="DivID" title="Title">
<iframe height="Size" width= "Size" src="http://RaspberryPi_IPAddress:1880/ui"></iframe></div>
```

Having discussed how to integrate the object-oriented IoT-enabled 3D models in the cloud, let us now turn to consider the performance simulation and prediction. Functions for performance simulation has been developed including threshold alerting and control, and warranty expiration reminder. Before carrying on threshold alerting and control, it is necessary to involve a dynamic performance simulation. Towards this end, a “contour” plotting function was called from Plotly.js. Plotly.js is a high-level, declarative charting library built on top of d3.js and stacj.gl (plotly, 2018). “Plotly.newPlot()” was used to plot the temperature with various colors in a 2D plan. The codes were given below:

```
var data = [ {z: z[m,n],type: 'contour'}];
var layout = {title: 'HVAC Management'}
Plotly.newPlot('DivName',data,layout,config);
```

On simulating the HVAC operational performance, several variables were defined. z[m,n] was defined as the location-based temperature value. It can be assigned with either predicted value or monitoring value. Another significant variable is the temperature change matrix x[m,n]. It was assigned with a combination of impacts from heat loss and HVAC interaction. Likewise, the HVAC impact was defined as HVAC_ Power[m, n], which was assigned with a combination of all HVAC impacts. When time goes, the temperature indoor keeps on changing. HeatLoss() function was made for simulating this change.

```
var z[m,n],x[m,n],HVAC_ Power[m, n];
HeatLoss ();
function HeatLoss () {z[m, n]= z[m, n] + x[m, n];}
function HVAC_Number_ON() {x[m, n]= x[m, n] + HVAC_ Power[m, n];}
function HVAC_Number_OFF() {x[m, n]= x[m, n] - HVAC_ Power[m, n];}
```

After defining the HVAC power, a dynamic control schema was established. The HVAC can be either controlled automatically or manually. The automatic control mode was sensor-based, and threshold control was configured as followings:

```
function HVAC_Number_THREASHOLD(){
if(Sensor[SensorNumber]<Tmax) { HVAC_1_On(); }
if(eee[SensorNumber]>=Tmin) {HVAC_1_Off();}
else{return;}
}
```

On the other hand, once the manual mode was selected, the HVAC can only run/stop when turning it on/off by the end users.

```
function HVAC_Number_CHECKBOX() {
var checkBox = document.getElementById("HVAC_Number_CHECKBOX");
var text = document.getElementById("HVAC_Number_ON");
if (checkBox.checked == true){HVAC_Number_ON();text.style.display = "block"; }
else {HVAC_Number_OFF(); text.style.display = "none";}
}
```

With a connection to HVAC control (both automatic and manual model) was made, the proposed web-based application was expected to predict/simulate the HVAC performance; regarding the warranty management, an expiration reminder was embedded in the proposed application. A warranty setting button was created in the menu of element property. The warranty time for each facility was specified by the end users.

```
<input id="Facility_Number_WarrantyTime" type="datetime-local">
<button id="warrantyButton" onclick="setWarrantyTime(this);">Set FacilityNumber Warranty
Time</button>
```

After that, a comparison was made between the expiration time and the current time. To this end, the date and time data should be reformatted to be comparable. Once the expiration time was smaller than the current time, the proposed supplication would alert the end users with a message to identify the expired facility.

```
var alarmTimer;

function setWarrantyTime(button) {

var ms = document.getElementById('Facility_Number_WarrantyTime').valueAsNumber;

if(isNaN(ms)) {alert('Invalid Date');return;}

var alarm = new Date(ms);

var WarrantyTime = new Date(alarm.getUTCFullYear(), alarm.getUTCMonth(), alarm.getUTCDate(),
alarm.getUTCHours(), alarm.getUTCMinutes(), alarm.getUTCSeconds());

var differenceInMs = WarrantyTime.getTime() - (new Date()).getTime();

if(differenceInMs < 0) {alert(Facility_Number +'Warranty has expired');return;}

}
```

Hence, as suggested by the focus group interview, we have developed an HVAC-centralized simulation/prediction function, while the functions for analysis can be extended for wider use in the future.

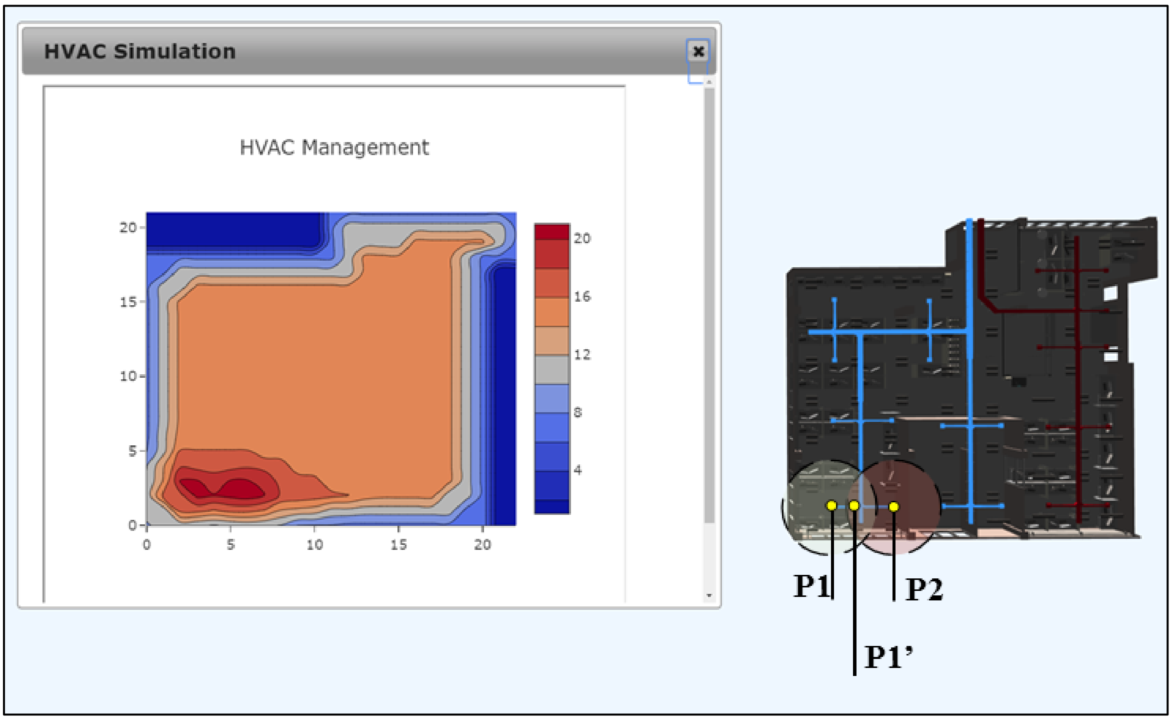


Figure 43 Dynamic HVAC Simulation (the New Zealand Building).

8.3 Summary

This chapter presents the outcomes of the working prototype development. This chapter began with a process model for the proposed system. Wherein, fours parts of work were divided. They are modeling, IoT deployment, database establishment, analysis integration. Then, a user-centralized design was made, and several end-user engagement workshops were established. Meanwhile, the development of each part was carried on separately in an agile way.

The results of such development answered the investigating questions (Q13-Q16) proposed in this study. The proposed system adopted SCADA level 4 by using relational database and WebGL library. Considering the state-of-the-art of the proposed technologies, SCADA Level 4 was adopted. Besides, a relational database was used paired with 3D visualization in WebGL. By adopting such a 3D web-based platform, the non-expert industry end users were expected to manage the building facilities at a higher convenience level. In addition, the parts of the proposed system were developed separately. To put it into another way, when one part of it evolves, it will be easy to replace with a new part without major updates on the rest parts. Applying on a pilot, the next chapter will evaluate the effectiveness of our proposed system.

Chapter 9 Results and Analysis from Pilot Testing

9.1 Introduction

The purpose of this chapter is to evaluate the effectiveness of the proposed system by analyzing the findings and results of the pilot testing in order to achieve Objective 5. The data collection process for the results of this chapter was presented in section 4.7. The pilot testing results are constructed by demonstrating the energy savings that were obtained from adopting the proposed system. In the coming section, the pilot case will be selected while the project information will be given. In the third section, the sensor layout was further discussed followed by that the simulation results for HVAC operation in three working modes will be presented separately. The heating costs for each mode were then calculated. Finally, the effectiveness of adopting the BMS and the proposed solution will be evaluated separately. This also distinguished the attributes from BMS features and others.

9.2 Project Information of the Pilot Case

As mentioned before, New Zealand smart buildings were not intelligent enough. In view of this, this research developed an IoT-enabled BIM-based BMS application. Before commencing the development, a focus group interview suggested that the first step of this research should focus on the HVAC management, which was the biggest cost and confort driver in New Zealand FM. Hence, a New Zealand building was selected as a case study. The proposed system was applied to this building for promoting HVAC performance. First, the BIM models were created in Autodesk Revit. The RVT file was transformed into a JSON file. Then, it was loaded into the proposed application (See in Figure 40). After that, the IoT prototype was deployed based on a master-slave pattern and embedded into the property of corresponding elements (See Figure 39). Next, a MySQL database was connected with the master (Raspberry Pi). The monitoring data were stored in relative tables. Last, an HVAC management function was integrated to simulate the HVAC performance (See Figure 43). Considering the generalization, this pilot case was selected based on three factors: building type, location, and accessibility.

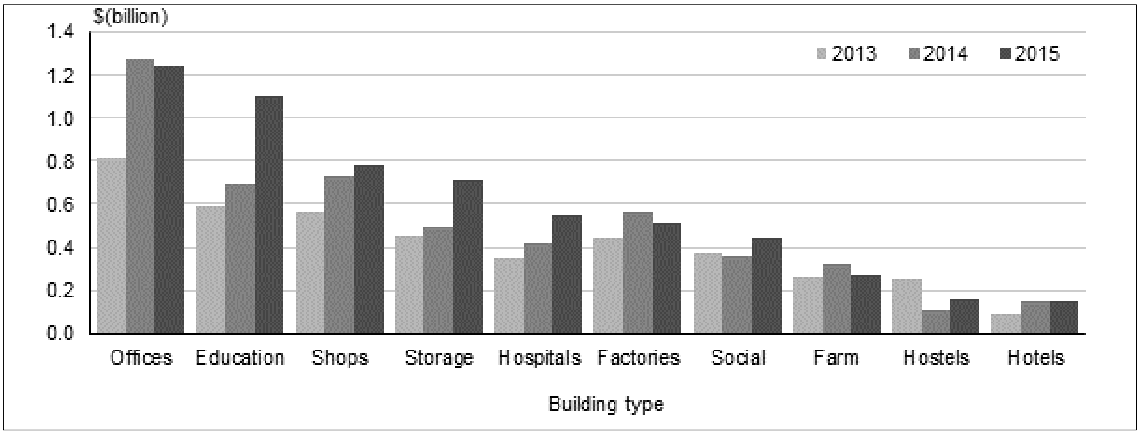
This research aims to investigate the effectiveness of BIM-BMS integration in managing existing educational facilities. That is to say, the building should be in New Zealand. Considering the generalization, the pilot case was selected among buildings in Auckland, the biggest city in New Zealand. At this moment, the integration of BIM and BMS is evaluated on the pilot case in its effectiveness in solving the contemporary issues in the New Zealand AEC industry.

The building sector has a diversity of building types, which vary the building features. Three criteria are used in building type selection. They are facility system complexity, operational time, and typical tenant type. Essentially, BIM is usually established in a building project for addressing complexity while most educational building, hospital building, commercial building, industrial building projects are complex enough (Cao, Song, & Wang, 2015). To meet the requirements for data collection for this research, the operational data should be measurable. Compared to accessing hospital building or commercial buildings for 24 hours, educational buildings are more achievable for a .Ph.D. programme.

Meanwhile, the tenant type should also be considered as a factor that influences the energy use. Self-owned, occupied and maintenance educational buildings are the most suitable for research purposes. However, commercial buildings usually deal with multiple tenants and will be difficult to generalize. That is because commercial tenant energy use, among tenants, is highly variable (Bennet & O’Brien, 2017).

As the second large attribute in non-residential buildings, educational buildings doubled their value of building consents in 3 years (See Table 18). Therefore, rather than examine all building types, this research prefers to limit its scope within educational buildings. Whereby, the pilot case was selected from educational buildings.

Table 18 Value of Non-Residential Buildings Consented (2013-2015).



Source: Statistics New Zealand (2016).

What we know about the benefit of BIM is largely based on empirical studies that investigate how effective the proposed techniques perform. As mentioned above, empirical data for post-construction BIM use is either non-existent or not rigorously validated in New Zealand. Hence, this research selects Building A (an educational building operates 24 hrs 7 days) as a case study and evaluates the effectiveness of the BIM-BMS integration on it by taking a regression analysis. The pilot case was an open room for postgraduate study (See Figure 44).

Figure 44 The Pilot Case.

The results of this research can be generalized to either educational buildings, or other building types with similar features in New Zealand. However, the results of this research cannot be used in small residential building projects.

There is a large range of factors influencing building sustainable performance. However, this study is unable to encompass the entire building performance indicators. After a literature review, three main factors, which are the most popular used in evaluating building facility operational and maintenance performance, are identified. They are building energy efficiency, building thermal comfort, and building facility maintenance-saving. Then, this research limits its scope within the energy efficiency on evaluating the HVAC operation systems on the pilot case.

The data collection was conducted in the selected pilot case in Auckland on 8/07/18. The indoor temperature was monitored, stored, and then "select" from the MySQL database. Heaters were deployed in the selected building. The operational thresholds of the thermostats were set between 20°C-25°C. Other building parameters were defined in Table 19.

Table 19 Parameters for the New Zealand Building.

Parameters	**Quantity**	**Measurements**
Building length	lenBuilding	20
Building width	widBuilding	20
Building height	htBuilding	4
Roof pitch	pitRoof	0
Number of windows	numWindows	35
Height of windows	htWindows	1.2
Width of windows	widWindows	1
The type of insulation used	kWall	0.038*3600
	LWall	0.2
Glass windows	kWindow	0.78*3600
	LWindow	0.01

	c	1005.4
The constant temperature of a heater	THeater	50
Density of air at sea level	densAir	1.2250
Electricity price	cost	0.2/3.6e6
Initial indoor temperature	TinIC	20

Due to the time consumption of collecting outdoor temperature for half a year in Auckland, we used the temperature data recorded by NIWA (2018) on an hourly base while the temperature data missed was complimented from another database available online such as MetService (2018), and The Weather Network (2018). The data was used for simulating the climates in Auckland during 01/09/2017-30/09/2017.

9.3 Sensors Layout in the Pilot Case

As illustrated in Figure 45, the room was divided into nine areas. There is one part that was not occupied, which has been excluded from this test. For the other eight parts, eight temperature sensors (#2-9) were deployed separately. Wherein, one temperature sensor (#2) was deployed near the BMS thermoset. The data collected from this sensor was expected to represent both the temperature in its area and the temperature measured by the BMS. Then, one additional sensor (#1) was deployed at the terminal of the HVAC, which represent the temperature measured by the traditional operation.

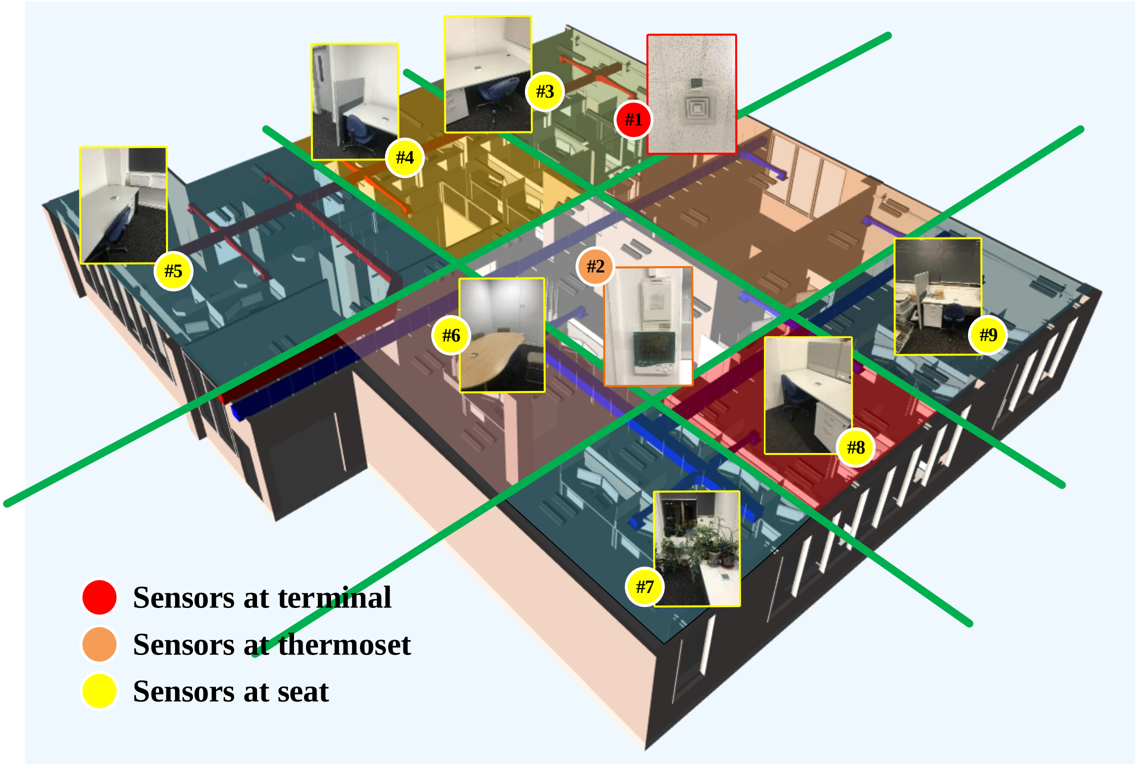


Figure 45 Sensor Layout of the Pilot Case.

9.4 Results from the Thermal Simulation

The indoor temperature data was collected from those nine sensors (See the data in Appendix C). Such data were collected on an hourly base for 24 hours. After that, two linear models were established for regression analysis carried on in SPSS. The model summaries for both were listed in Table 20 and Table 24. The analysis of variance (ANOVA) for both was listed in Table 21 and Table 25. Based on these results, the relationships between T_{te}^{m} and T_{in}^{m}, and T_{bms}^{m} and T_{in}^{m} were given separately.

Table 20 Model 1 Summary.

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.450[a]	0.203	0.167	5.53430

a. Predictors: (Constant), T_{in}^{m}.

Table 21 Model 1 ANOVA[a].

Model		**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
1	Regression	171.442	1	171.442	5.597	0.027[b]
	Residual	673.827	22	30.629		
	Total	845.270	23			

a. Dependent Variable: T_{te}^{m}.

b. Predictors: (Constant), T_{in}^{m}.

Table 22 Model 1 Coefficients[a].

Model		**Unstandardized B**	**Coefficients Std. Error**	**Standardized Coefficients Beta**	**t**	**Sig.**
1	(Constant)	-321.321	147.443		-2.179	0.040
	T_{in}^{m}	16.056	6.787	0.450	2.366	0.027

a. Dependent Variable: T_{te}^{m}.

As presented in Table 22, a_{te} = -321.321, and b_{te} = 16.056. Hereby,

$$T_{te}^{m} = -321.321 + 16.056 * T_{in}^{m} \text{ (Eq. 14).}$$

The relationship between the measured temperature and the simulated temperature in the terminal was plotted in Table 23. Since *R* = 0.450 (0.300 to 0.500), the linear relationship strength is moderate. Hence, the relationship can be simulated with a linear equation.

Table 23 a Comparison between the Measured and Simulated Temperature in the Terminal.

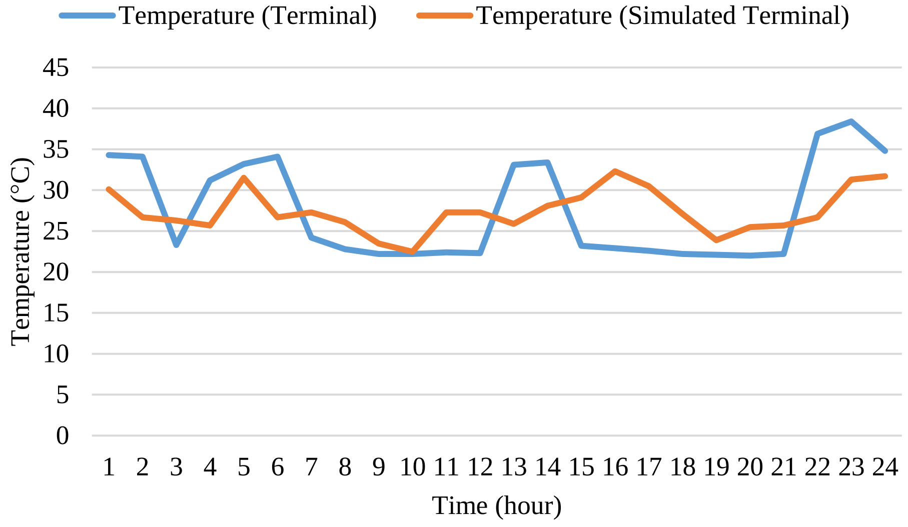


Table 24 Model 2 Summary.

Model	**R**	**R Square**	**Adjusted R Square**	**Std. Error of the Estimate**
1	0.686[a]	0.470	0.446	0.18939

a. Predictors: (Constant), T_{in}^{m}

Table 25 Model 2 ANOVA[a].

Model		**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
1	Regression	0.700	1	0.700	19.528	0.000[b]
	Residual	0.789	22	0.036		
	Total	1.490	23			

a. Dependent Variable: T_{bms}^{m}.

b. Predictors: (Constant), T_{in}^{m}.

Table 26 Model 2 Coefficients[a].

Model		**Unstandardized B**	**Coefficients Std. Error**	**Standardized Coefficients Beta**	**t**	**Sig.**
1	(Constant)	-0.401	5.046		-0.079	0.937
	T_{in}^{m}	1.026	0.232	0.686	4.419	0.000

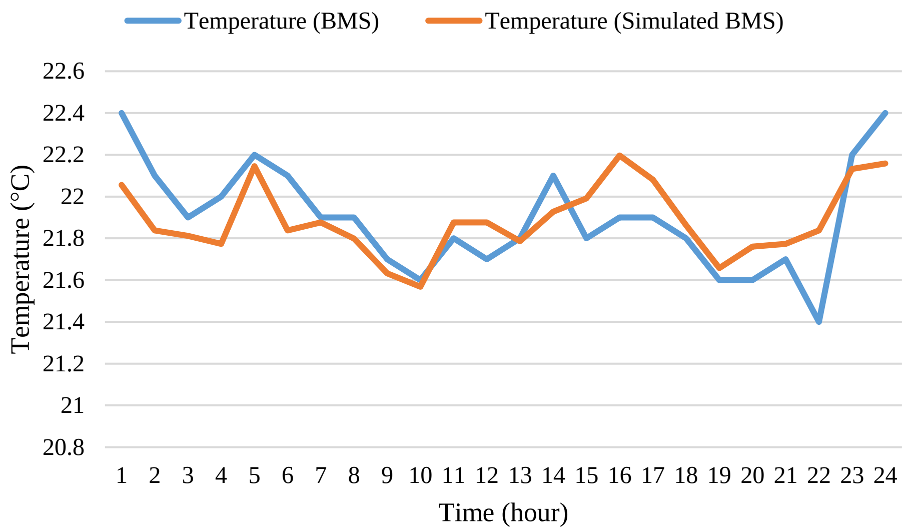
a. Dependent Variable: T_{bms}^{m}.

As presented in Table 26, a_{bms} = -0.401 and b_{bms} = 1.026. Hereby,

$$T_{bms}^{m} = -0.401 + 1.026 * T_{in}^{m} \text{ (Eq. 15).}$$

The relationship between the measured temperature and the simulated temperature in the BMS was plotted in Table 27. Since R = 0.686 close to 1.000 (0.500-1.000), the linear relationship is strong. Hence, conducting a threshold control based on the BMS is acceptable whereas there is still potential to be promoted.

Table 27 a Comparison between the Measured and Simulated Temperature in the BMS.



To simulate the operation of the HVAC system in the three working modes on the pilot case, we adapted our Simulink models from the “thermal model of a house” established by The MathWorks (2018) (See Figure 46). The heat flow into the room is expressed by the Eq. 4. While the heat losses and the temperature time derivative are expressed by Equation 2. As illustrated in the Simulink models, thresholds (T_{min} to T_{max}) were set for controlling the HVAC. The HVAC will start to heat once $T_{measured} \leq T_{min}$ while the HVAC will be turned off when $T_{measured} \geq T_{max}$. After that, the $T_{measured}$ in the three models will be processed after inputting the real-world T_{out}. The operation costs *C* for the three working modes can be calculated separately based on the electricity price of New Zealand at the time be calculated. Therefore, the dependent variables are determined as the operating costs *C*. Then, the outdoor temperature was inputted (See Figure 47). Ultimately, the results of those three costs were obtain in Figure 48. The energy savings was calculated separately for both the proposed system and the BMS alone. By adopting the used of BMS alone, the heating costs were saved by 1.52% whereas adopting the proposed system attributed a further 0.68%, 2.20% in total.

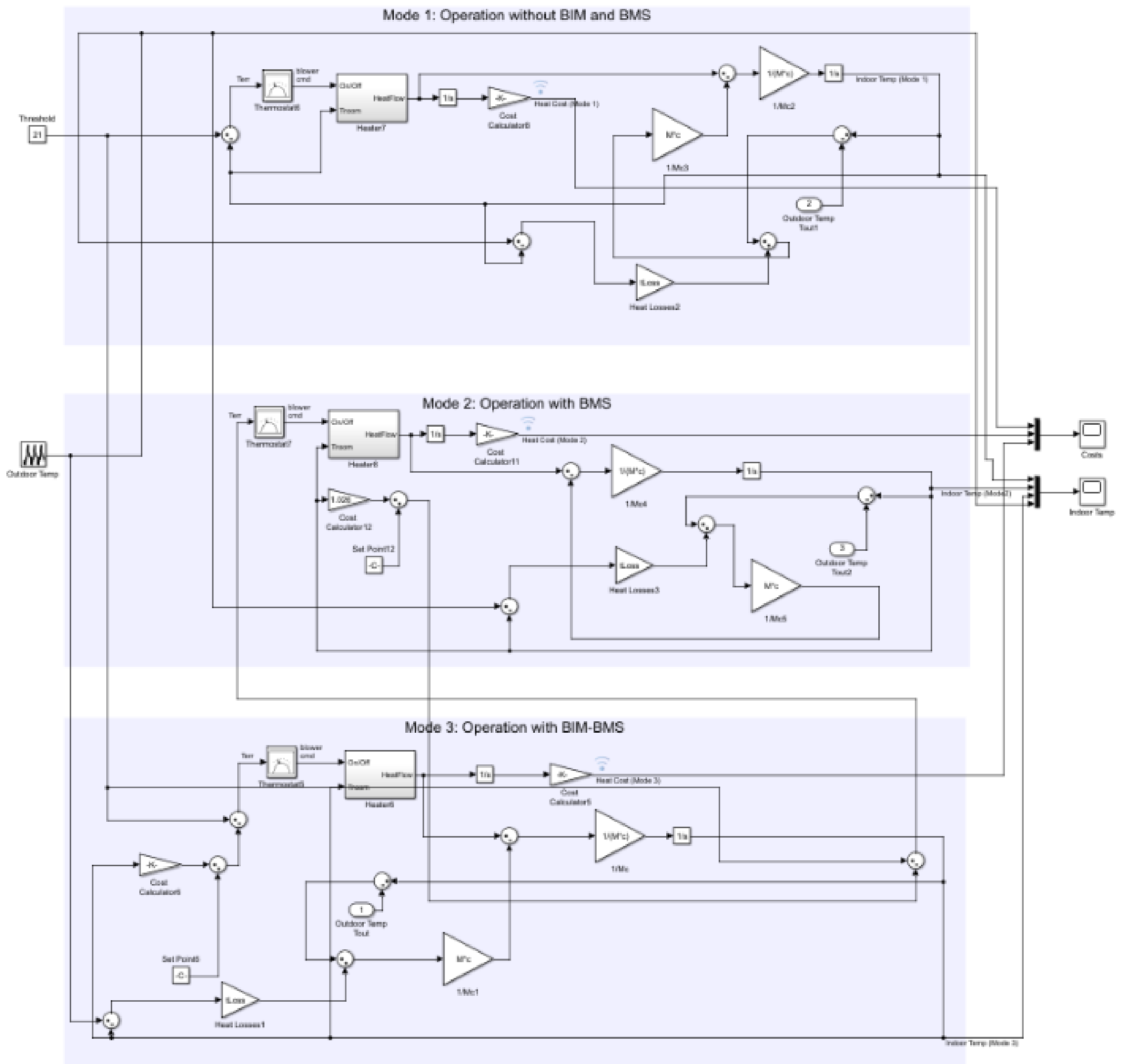


Figure 46 the Simulink Model for the Three Operational Modes.

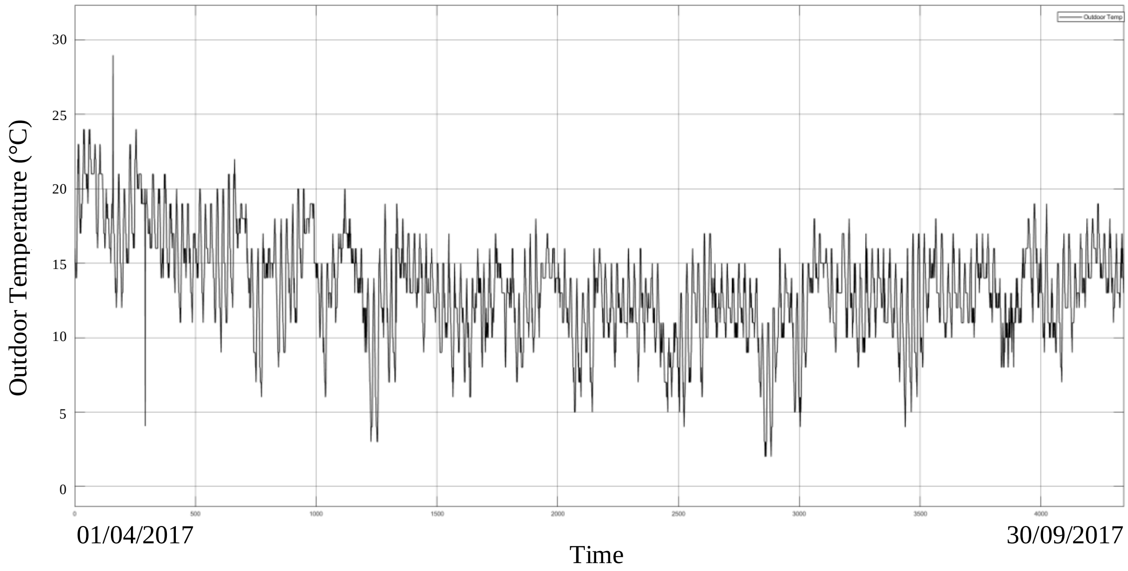


Figure 47 Outdoor Temperature in Auckland during 01/04/2017~30/09/2017.

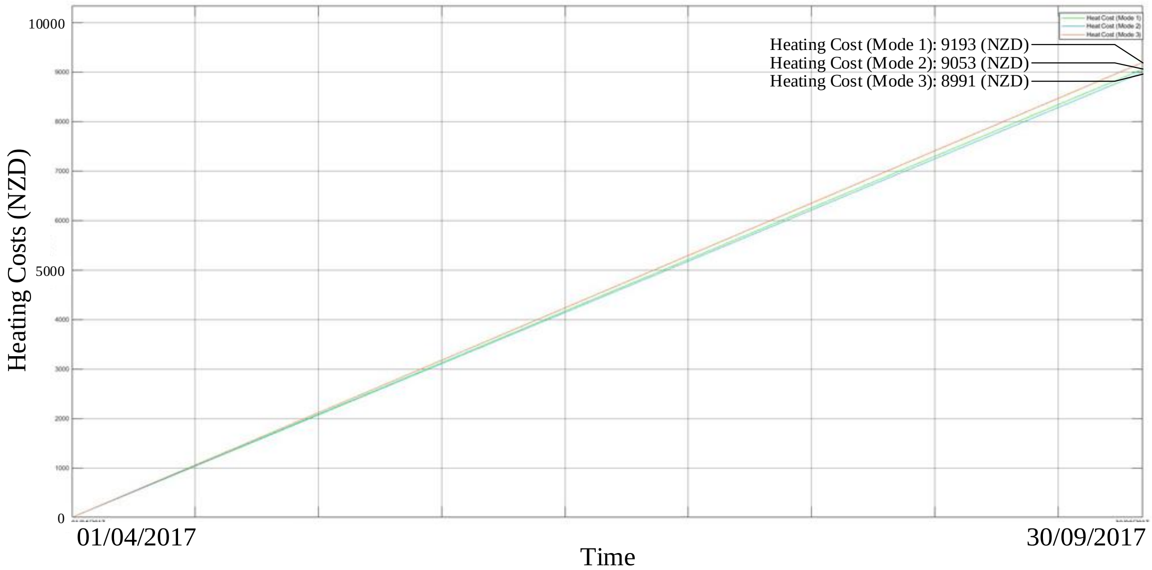


Figure 48 Heating Costs (NZD) during 01/04/2017~30/09/2017.

9.5 Evaluation of Energy Efficiency

Several benefits from using BMS were already demonstrated from the literature coupled with the focus group interview, which were further confirmed in this pilot test. In the first place, BMS acquired the monitoring data from sensors for conducting supervisory controls towards improving energy efficiency. As shown in Table 26, the linear relationship between mean indoor temperature and the temperature obtained by BMS thermostats is strong. Hence, it is efficient to conduct supervisory control by using the temperatures monitored in BMS thermostats. As plotted in Figure 48, 1.52% of the heating costs were saved by the use of the BMS. Besides, the BMS carried on condition monitoring for the facilities. Such monitoring data was used for preventing operational failures. Whereby, this will reduce the maintenance costs.

Also, with smart monitoring and control of the built environment, BMS is capable of facilitating the smart infrastructure. To promote the smart grids, making building smart was one of the pre-conditions. There is a need for communication between smart grids and smart buildings.

Next, with the deployment of responsive sensors, the indoor thermal environment was maintained in the occupant comfort zones. Last, the most obvious usage of a BMS was to simplify the building operation. The FM team can carry on supervisory control in the cloud coupled with several dashboards visualizing the indoor climates. While local control can be made by the occupants within a simple app on their phones. Therefore, by adopting BMS, the efficiency of FM can be largely enhanced. The effectiveness of BMS for FM in the pilot study was evaluated in Table 28.

Table 28 Effectiveness of BMS for FM.

Aspects	**BMS**	**Effectiveness**
Energy efficiency	SCADA	BMS utilized the data acquired for conducting supervisory controls towards maintaining the energy conservation.
Maintenance cost savings	Preventive maintenance	BMS provided condition monitoring for the facilities to provide prevention of failure.
Lower utility costs	Connection to utilities	The BMS can be connected to the smart utilities such as smart grids.
Occupancy comfort	Stable indoor climates	BMS provided threshold-based controls which reduced the complaints from occupants.
Simplified building operation	Smart controls	BMS provided remote monitoring and automatic controls for the end users.

In contrast to merely applying BMS, the proposed system provided additional promotion on these features in BMS. First, by analyzing the monitoring data, a better operational scheme was obtained. Such an optimized scheme was expected to bring a further 0.68% heating cost saving. Second, the condition monitoring data was processed, and operational faults were detected. Wherein, the fault facilities were isolated, and the potential solutions were retrieved from similar past cases. This furtherly reduced the maintenance costs. Third, the proposed system enabled the smart infrastructure by providing detailed documentation management. Such documents included texts, graphics, audios, and videos. Wherein, BIM was engaged in managing those documents. In terms of this, BIM models were capable of being connected to the utility models. For instance, the underground pipes were connected to the water distribution networks. This benefited the maintenance of the distribution networks by providing an accurate 3D plan for the underground pipes.

The BMS was conducted based on the assumption of perfect mixed air, whereas the inhomogeneous indoor air caused the wastes from the inaccurate measurement of the indoor thermal environments. With the help of the proposed system, the thermal environments were analyzed. The results were used to further maintain the occupant comfort.

Last, despite the centralized control provided by BMS, the end users might be immersed in the massive number of data streams. Facing this issue, the proposed system provided a 3D human-computer user interface. Such interface made possible for the non-expert users to efficiently manage the proposed system. Therefore, the use of the proposed system can further facilitate the efficiency of BMS. The effectiveness of the proposed system for enhancing BMS in the pilot study was evaluated in Table 29.

Table 29 Promotion of BMS Obtained from the Proposed System.

Aspects	ND BIM-IKBMS	Effectiveness
Energy efficiency	SBSC	The proposed system analyzed the monitoring data and optimized the operation from the simulation.
Maintenance cost savings	FFSC	The condition monitoring data was further processed for fault detection and diagnosis.
Lower utility costs	Building descriptions	The proposed system promoted the connection between BMS and smart utilities by providing rich information, such as underground conditions.
Occupancy comfort	Thermal comfort analysis	The proposed system analyzed the occupant thermal environment to avoid of the influence of inhomogeneous indoor air.
Simplified building operation	3D visualization	The proposed system visualized the FM processes in a 3D environment, which can be easily understood by non-expert users.

To evaluate the effectiveness of using the proposed system, this study also adopted an assessment model for evaluating FM performance from Codinhoto and Kiviniemi (2014). Numbers of aspects were identified as potential benefits. Such as data richness, life-cycle view, roles or discipline, business process, delivery method, timelines/response, change management, graphical information, spatial capability, information accuracy, interoperability, overview. By adopting the proposed system in the pilot case, the effectiveness was evaluated (See Table 30).

Table 30 Effectiveness of ND BIM-IKBMS (BMS Attributes Not Included) for FM.

Aspects	ND BIM-IKBMS	Effectiveness
Data richness	2D drafting 3D entities 4D time 5D cost 6D project lifecycle information	Floor plan retrievals with location-based identifiers; spatial element retrievals with GUID identifiers; working sequence attached on corresponding entities; cost estimations on corresponding entities; project lifecycle

		information linked with the object name.
Life-Cycle view	Design Construction Post-Construction Deconstruction	Data on life expectancy and replacement costs from designers and contractors were embedded in post-construction BIM models.
Roles or discipline	Occupancy Ownership Management Development Execution	The system managers allocated different authority to project stakeholders (disciplines).
Business process	Cross-Departmental integration	Features were provided such as document control, instant messaging and the ability to mark up and review model files directly within the CDE.
Delivery method	IoT	An IoT-enabled platform was delivered embedding BIM models, asset documents, etc.
Timelines / Response	4D maintenance sequencing	The requests for maintenance from the inspection were progressed in the proposed system; the maintenance activities were sequenced by allocating to the corresponding building elements in the proposed system.
Change management	Parametric modeling	The interlinked attributes were capable of automatically changing their features.
Graphical information	GUID IP address/Hostname	3D building elements are embedding unique webpage references generated by corresponding e-documents; sensor data plotting interfaces with unique IP addresses.
Spatial capability	3D Space management	BIM was utilized to effectively distribute, manage, and track appropriate spaces and related resources within a facility.
Information accuracy	LOD	As-Built models were assigned with specific LOD; the information was updated timely.
Interoperability	COBie / IFC OmniClass MQTT/CoAP	The standardization of the proposed system eliminated the diversity of data formats, naming convention, and communication protocols.
Overview	Integration	The proposed system of integrated building automation, description,

knowledge, performance, and inspection in a single interface.

First, by adopting the proposed system, the data richness was enhanced. Data richness refers to the amount of detail contained in a piece of textual, graphic, audio, or video information (Xu, Lu, Zeng, Xu, & Li, 2019). The data embedded in our system included 2D floor plans, 3D spatial elements, 4D working sequence, 5D cost estimations, and 6D lifecycle information. The data mentioned were managed in an object-oriented database index with a specific identifier (Xu et al., 2019).

Life-cycle views were emphasized by the owners both economically and ecologically. With proper building lifecycle management, the proposed system provided relevant information about the current building conditions and enabled the analysis of alternatives.

The BMS was used by the operators who might limit the engagement of other roles. Facing this issue, the proposed system was developed as a multi-stakeholder-engaged platform. Roles involved in the building project throughout the whole lifecycle were allocated with specific authority for using our system. In results, the building information was updated timely while the conflicts between different organizations were removed by the system moderator.

The proposed system provided a CDE. Working in a CDE, the business process can be facilitated. Typical features included document control, instant messaging and the ability to mark up and review the 2D/3D model in real time. This made possible for the cross-departmental cooperation centralized on an integrated platform.

The proposed system adopted an IoT SCADA framework. In contrast to the traditional documentation, all data was stored in the cloud and access by a particular authority. The delivered as-built documents were upload into the cloud and allocated with unique webpage links to access.

The conventional asset management processes urgent timely maintenance. The proposed system embedded a repair request system which connected to the 4D time information. Once a facility confirmed for repair, the activities coupled with their schedules will be assigned to the corresponding elements by the end users.

The inconsistency among the documents from different stakeholders exacerbates the weakness of the conventional information management processes facing to changes. The proposed system adopted a parametric modeling process for maintaining all the documents in a centralized base. Parametric modeling refers to the process that the stakeholders utilized computer to establish or maintain an information model with attributes from real-world behavior. Wherein, the attributes are interlinked with each other. That is to say, once one parameter changed, all the documents related to such a parameter will adapt to this change automatically. By adopting such a process, the proposed documentation system was more flexible to the changes.

The traditional 3D game engine always reconstitutes the entire building elements in a single entity. Such entity was then rendered with an entire texture. However, this limited the object-oriented capacity of the model. In light of this, the proposed system remained the object-oriented models and allocated a GUID for each element. Under each element, documents were attached by a simple website reference. As for the dashboards, specific IP addresses/Hostnames were involved under the corresponding element as well. Hence, rather than a simple 3D shape, the proposed system followed an object-oriented hierarchy for managing all graphic information.

Traditional space management is limited in planning on a 2D layout. In contrast, the proposed system was efficient in managing spaces in 3D models. With the help of BIM, the end users were able to distribute, manage, and track appropriate spaces and related resources within a building. That is to say, the BIM models were used for analyzing the existing space use and planning for applicable changes. This provided a proper allocation of spatial resources throughout the entire asset lifecycle.

A benefit of adopting the proposed system is that the information accuracy was enhanced. Information accuracy refers to the correctness of the output information. As-Built models in our system were assigned with specific LOD. The LODs were designated by the owner or the operation team. With appropriate LODs, the elements were expected to meet the information accuracy. Besides, the information was updated timely. As mentioned before, once one changed, the others will adapt. Hence, the information accuracy for the information management processes in O&M was largely enhanced.

The diversity of data formats, naming convention, and communication protocols exist among the information management processes. The best way of improving operativity was to standardize them. Towards this end, the proposed system adopted IFC formats to minimize the redundancy from repeating works. As for the communication among devices, the proposed system used MQTT, an ISO communication protocol, to reduce the complexity of the communication processes. Meanwhile, the naming system can be consistent by using OmniClass. Whereby, the interoperability was enhanced. Finally, the BMS provided a centralized control for the end users, however, merely for controls. There is a need to integrate all kinds of system.

With this in mind, our system of integrated building automation, description, knowledge, performance, and inspection in a single user interface. Such interface provided an overview of the entire systems. Therefore, the use of the proposed system can largely promote the efficiency of FM. The effectiveness of BMS for FM (exclude the effectiveness of enhancing BMS) in the pilot study was evaluated in Table 30.

9.6 Summary

This chapter presented the results and findings of pilot testing gained from the linear analysis in SPSS and the thermal simulation in MATLAB. The findings answered the investigating questions (Q17-Q20) proposed early in this study. The tangible functions direct to energy savings were demonstrated with a comparison among HVAC simulations three operational modes. The attributes from BMS was identified as 1.52% while the other features attributed a further 0.68%. A detailed evaluation of operating BMS and the proposed system was made separately. A specific evaluation of how the proposed system benefits BMS was carried on at the same time. Such results provided insight into the generalization of the proposed system. Till now, all the results have been presented. In the next chapter, we will align the results to the objectives plus providing a comparison with findings by other researchers.

Chapter 10 Discussion of Results

10.1 Introduction

This chapter synthesizes the research findings from both qualitative and quantitative data collection. The synthesis is presented so that it answers the investigating questions and delivers the research objectives that will be presented in the next chapter. This chapter follows the order of the demonstration route illustrated in Figure 7 (the blue arrows) for achieving the objectives. Prior to commencing the synthesis, the nature of the problem will be restated. To begin with, this chapter will validate the efficiency of the proposed solution by a discussion of the pilot testing results. After that, the efficient solution will also be verified in effectiveness in removing the barriers in the New Zealand context. It will then go onto remove all the barriers and the solution will be demonstrated to be capable of solving the research problem. For generalization, this chapter also provides a comparison between the findings and the wide literature. The testing results will be reviewed comparing other tests with similar purpose.Then the working prototype will be analysed with a comparison to the hardware/software solutions established by others. Finally the proposed framework will be discussed to distinguish it from other frameworks.

10.2 Nature of the Research Problem

From the literature, the problem of current building O&M information management was indicated as complexity (Becerik-Gerber et al., 2012). Facing this problem, this study aims to improve the effectiveness of building O&M information management in New Zealand. The findings of this study were expected to be generalized to the educational buildings in New Zealand but were not demonstrated efficient to be used in a global context. On commencing the literature review, the potential solution was identified as the adopting of BIM-BMS integration. Other solutions that might also be capable of improving the effectiveness of the building O&M information management were not included. As for the sustainable performance, only the energy saving was measured and compared to the traditional operation system. Other sustainable performance improvements such as thermal comfort, maintenance efficiency, etc. were not tested in this study.

10.3 Investigating Questions

10.3.1 Documentation Analysis Findings (Q1-3)

In the documentation analysis, the BIM related concepts were defined. The findings indicated that the current BIM definitions coupled with its maturity levels were not sufficient to eliminate the disputes in proposing BIM into the New Zealand context. In this regard, this study provided a New Zealand specific definition of BIM. Meanwhile, the BIM maturity levels were refined in a New Zealand context. Based on the data analysis all hypotheses were accepted which means the maturity levels are efficient to represent the BIM adoption process in New Zealand. In addition, the barriers for each level were obtained separately. The outcomes were expected to remove the inconsistency in New Zealand BIM research.

Q1: How should BIM be defined in a New Zealand context?

After a review of the existing BIM definitions, we found that there is a miss match on:

(1) Involving the analogical information.

(2) A consideration of multi-project interoperability.

Nowadays, there is an increasing demand in New Zealand on managing such analogical data in BIM platform towards bridging the gaps between BIM and building operation. Besides, the engagement of multi-project interaction forms the pre-condition of smart cities, digital cities, and responsive cities in New Zealand. Whereby, BIM in the New Zealand context should be defined as:

Building Information Modelling is a process of creating, sharing, exchanging, integrating, and managing digital and analogical representations with multiple dimensions, in multiple disciplines, by multiple stakeholders, at multiple lifecycles, for multiple projects.

Q2: How can BIM maturity levels adapt to a New Zealand context?

In analyzing the documents, we found numbers of issues in generalizing existing BIM maturity levels into a New Zealand context:

(1) The traditional maturity levels classified as CAD tools in BIM Level 1. However, 3D CAD tools (e.g. Solidworks) were popularly used in the New Zealand AEC/FM industry. In this regard, we provided a more detailed classification by allocating 3D CAD to facilitate multi-task responsiveness in the BIM Level 1 while remaining instrument sketching and 2D CAD at BIM Level 0.

(2) New Zealand government did not mandate BIM in the construction sector. This brought the insufficient number of BIM models for existing buildings in New Zealand. This will lead to a gap to achieve BIM Level 4. Despite some of the companies already achieve the BIM Level 3 technically. Hence, an updated BIM Level 4 is needed for obtaining enough BIM models before interconnecting them.

Whereby, BIM maturity levels in the New Zealand context should be defined as:

(1) BIM Level 0.0: outputs in the same discipline are made separately, and once one changes, the corresponding outputs cannot be updated automatically.

(2) BIM Level 1.0: outputs in the same discipline are responsive with each other, and there are no gaps within one discipline, however, gaps exist among different disciplines.

(3) BIM Level 2.0: people in one team can federate multi-dimensional works in all disciplines together.

(4) BIM Level 3.0: people from all stakeholders are able to collaborate all discipline works in a multi-dimensional repository throughout the whole lifecycle.

(5) BIM Level 4.0: BIMs from multiple projects are interconnected, which enables the interaction in knowledge, spatial, economic, society, industry, etc.

Q3: What are the barriers paired with the potential solutions for practicing BIM in each maturity level?

After WFB analysis by year, we found that the BIM barriers in each maturity level were different. In comparison to the traditional barriers identified in an one-by-one way, this study provided a list of both technical barriers and financial barriers in different stages in New Zealand.

Technically, BIM barriers were identified as four aspects: tools, specifications, benchmarks, and paradigms. In the first place, the lack of software was the barrier in BIM Level 0.0. Next, in BIM Level 1.0, basic algorithms were developed to facilitate 3D visualization, crash detection, etc. to facilitate people separately. Despite this, a lack of cooperation urgent the need of certain specifications. Then, several BIM platforms embraced the BIM Level 2.0, which provided a shared model for multiple team cooperation. Nevertheless, a lack of benchmarks enlarged the risk for project failure whereas a lack of experts coordinating the BIM processes aggravated this situation. Once achieving BIM Level 3.0, CDE was established for interoperating those tools in order to manage a shared project repository. Despite this, legal issues became the main barrier for sharing and using the BIM models among different stakeholders. Last, the legal was well defined so that BIM models from different projects were able to be interconnected properly. Notably, the data scale within those tools should be reduced to achieve a higher level of BIM use -- IoB.

Financially, BIM barriers were clarified as four parts: resistance to culture change, initial costs, ROI, and BIM adoption. When BIM was first introduced to the AEC/FM industry, a culture change for the engineers was delivered. In spite of this, a lack of individual demand formed the resistance. After that, by adopting proper BIM solutions in BIM Level 2.0, the engineers began to make attempts to improve their working efficiency. In spite of this, high initial costs arose the barrier on demand from organizations, including training, software, and hardware costs. Next, the clients were gradually engaged in BIM Level 3.0, even though they did not see any tangible ROI. Since the application of building lifecycle management, the clients began to see the proven good ROI on BIM. Despite this, various clients from different projects were not interconnected without government promotion. Finally, the IoB might not be achieved until the government demand was met.

10.3.2 Focus Group Interview Findings (Q4-8)

After a thematic analysis gained from the focus group interview, the specific barriers coupled with the specific suggestions were obtained. The specific barriers in New Zealand were identified as:

(1) Low BIM adoption in operation phase.

(2) No empirical data of operational BIM use.

(3) The majority of current HVAC systems in New Zealand educational buildings are not energy efficient.

(4) Few BMS-based HVAC systems were adopted in New Zealand educational buildings but still not intelligent enough.

(5) ROI of BIM-BMS was not approved.

The specific suggestions for developing a BIM-BMS integration for managing existing educational facilities in New Zealand were identified from the focus group interview as:

(1) The HVAC system is the biggest driver for both cost and comfort in educational building O&M in New Zealand, which should be tested with a priority.

(2) Both of the temperatures measured by the traditional HVAC and the BMS are not the mean indoor temperature.

(3) IoT should be adopted towards a higher efficiency.

(4) Involving a building performance analysis in real-time operation might bring energy savings.

Q4: What is the relationship between BIM and BMS?

From a micro BIM perspective, BIM and BMS are totally different things, hence BMS is not a part of BIM at all. BIM is used for documentation whereas BMS focuses on the building performance. Despite, BIM should deliver information to the BMS. From a macro BIM perspective, BMS is a smaller subset function of a lager BIM process model. At this point, there is no real traction around the concept of BIM, BIM as a process, or BIM as an output in New Zealand. This made the evaluation process complex. There is a need to distinguish the attributes from BIM and BMS separately. Whereby, an evaluation scheme on the effectiveness of BMS, promotion of BMS obtained from the BIM-BMS integration, and the effectiveness of the BIM-BMS integration excluding BMS was determined.

Q5: What is the current BIM adoption in New Zealand?

From the literature perspective, two facts have been indicated. Firstly, in terms of adoption, BIM in New Zealand is fast developing but still at a disadvantage. Secondly, BIM use in post-construction phase is crucial for a complete building lifecycle application to achieve BIM level 3.0, however, currently the weakest in New Zealand. On the other hand, we re-evaluate the New Zealand BIM adoption in the focus group. The BIM adoption rates for operation in New Zealand in those surveys are confirmed true and stable. However, it is hard to change. To put it in another way, all agreed that BIM is not fully used by a long way in New Zealand. Provided that, BIM in New Zealand is just about a few showcases. Those BIMs are only used for digitalization, specifically documentation. Yet their models have never been used by the operator in New Zealand. What's worse, there are no BIM software solutions for building O &M.

Q6: Is the BIM-BMS integration significant in supporting FM in New Zealand?

Nowadays, there is no value proposition for an operator of going the extra mile (and cost) to operate and maintain a fully integrated BIM model. BIM benefits the design and construction phases in New Zealand, while no real-world evidence shows that BIM benefits the O&M phase. This is consistent with the financial barriers identified in the documentation analysis that such a value proposition can only exist in the BIM Level 3.0 or above. Despite this, at this stage in New Zealand, BIM potential exists with the function of 3D visualization and documentation in the building operation phase. It might be more convenient to navigate a BMS linked to condition and maintenance history data within a pictorial format. Meanwhile, it will be more convenient for the operators in decision-making by comparing the BMS data with design objectives in BIM models. To achieve this, facility operators should be upfront in the early design phases. In addition, a variety of scenario modeling should be made in the design and construction phases. Also, it was also suggested that with efficient utilization of space, appliances paired with performance measuring, the operators are expected to identify what's working, what's performing quickly. Besides, bridging the gaps between BIM and BMS can get BIM onto a further maturity level.

Q7: What are the current limitations for BMS without BIM?

As an energy-efficient solution, BMS provided both smart monitoring and automatic control for building operational facilities. This benefits the FM people by representing energy consumption profiles in a meaningful visualized way. Wherein, a historical energy performance track provides a more comprehensive understanding of energy use for non-expert staff. Despite this, the main weakness of BMS has been identified from the literature - the failure to address data analysis and structuring. Without data analysis, raw data is fragmented. Capturing and reporting fragmented data can hardly help to promote a more sustainable post-construction performance. Also, the unstructured data stream issue challenges the BMS users by its overwhelming amount. Therefore, BMS has exceedingly limited practicality in promoting post-construction sustainability without BIM.

To obtain New Zealand specific findings, we also made a triangular check in the focus group interview on this question. A number of limitations were identified from the focus group:

(1) Cost. The ROIs of installing BMS is not clear whereas the initial outlays for BMS are high. Additionally, the savings in O&M phase are not easy to be measured. Provided that, the costs for O&M are usually different from what been designed. Then again, the building owners do not want to spend money on those savings as the tenants pay for that.

(2) Change management process. The biggest challenge in change management is the update and maintenance for BMS itself. However, changing management processes are missing in the New Zealand FM industry. Following occupancy, human interactions on the facilities keep on conducting. Then again, the BMS will perform inconsistently. Significantly, retrofits will largely attribute to such change.

(3) Big data. There is a tendency to abuse BMS in New Zealand. Too much noise exists for the processes. In New Zealand educational buildings, alarms are

frequently set in an inaccurate way before the BMS operation. Then again, the operators have to confirm and close it once BMS alerted. As the BMS operates 24 hours 7 days per week, the operators will be merged in a large number of alerts.

(4) Lack of intelligence. Despite a building can be smart by the BMS adoption, there is no intelligence in BMS. Provided that, BMS is a control system which takes actions only based on the inputs. Such a control system is limited in responding to the scenario when something is mechanically wrong. Having said that, currently, most of the BMSs for HVAC in New Zealand operate with a daily schedule. Such systems even work during the weekends when no one there. Particularly, two HVAC in the same room might be heating and cooling separately at the same time.

Q8: Why are the current BIM-BMS integration cannot satisfy the expectations?

In the literature, BIM is identified as a multi-dimensional building facility information database. It provides structured information management solution throughout the whole building lifecycle. It is capable of improving the fragmented data. Meanwhile, BIM has the capacity for nD simulation and analysis. Towards this end, numbers of researchers begin to use BIM models to bridge the gaps between BMS and data analysis, and BMS and data structuring. However, most of the projects only scrape the surface of BIM, and these projects fail to take full advantage of nD BIM capacity for BIM-BMS integration. The main problem of this phenomenon comes from unstandardized modeling outcomes. Five issues were identified from the literature: (1) some BIM models need to be detailed/developed; (2) BIM models need to be simplified into a lightweight model; (3) non-standard modeling process decreases the accuracy of information; (4) unable to access all parts of a BIM model leads to limited use of information; (5) lack of timely updates in BIM causes the miss of consistent information. Above all, currently pairing with unstandardized BIM models leads to the limited practicality of current BMS systems.

To obtain New Zealand specific findings, we also made a triangular check in the focus group interview on this question. Several negative comments about the use of BIM and BMS in New Zealand were indicated. A common view was that the BIM-BMS integration is theoretical and not practical. Wherein, two aspects were then considered: the technical readiness, and the initial costs. Regarding the readiness, the current immature PPP was identified as a barrier.

(1) Product.

Currently, there are no BIM software solutions for building O &M in New Zealand. On condition that BIM is truly silo. Predictive modeling hasn’t been integrated to BIM in New Zealand. On the other hand, BMS products in New Zealand are not reliable. Additionally, these products suffer from software versioning, various protocols.

(2) People.

The BIM-BMS integration is not scalable as it needs both BIM and BMS knowledge. Currently, facility managers in New Zealand struggle to manage the BMS. That said, bringing another complexity - BIM, on top of it makes it more difficult. Then again, BIM models are not established from an end user perspective.

(3) Process.

The BIM-BMS integration is technically difficult and financially expensive. Provided that, the only way for BIM-BMS integration is upfront. Despite this, in New Zealand, FM is not involved in building design and construction processes. What’s worse, the margin costs in the early stage are very small or non-existent. On the other hand, the majority of the existing buildings in New Zealand might not have BIM models. Only a few new buildings in New Zealand have their BIM models established.

When talking about the costs, the high initial costs for modeling and the long-term maintenance costs for such models were identified as one of the biggest roadblocks. A number of issues were identified regarding the costs for the BIM-BMS integration.

(1) High initial costs will be a barrier to the BIM-BMS integration adoption. To put it in another way, modeling a BIM in the operating phase is not cost-effective. Then again, the box-thinker operator will not get payment from the energy savings. Hence, the end users do not like to fund the initial costs.

(2) Keeping BIM and BMS up-to-date is a cost driver. From time on, operators keep on making changes unknowingly and just for convenience: they break linkages and change settings. A time after occupancy, the proportion of BIM and BMS will be decreased. In other words, analysis is inconsistent. Hence, a data manager is needed to maintain BIM models up to date.

10.3.3 Axiom Design Findings (Q9-12)

At this stage, we conduct a conceptual framework formation for the nD BIM-IKBMS. After an axiom design for the solution, several outcomes were achieved:

(1) To identify the functional requirements for the proposed system to fulfill the expectations, this research used the Axiomatic approach for the nD BIM-IKBMS functional design. The A0-level framework of nD BIM-IKBMS is designed to reduce the post-construction energy consumption by intelligent controls and historic retrievals. Then, the proposed system has been developed into five modules. Each module has been classified into several evolution levels or options. Prior to applying the proposed framework for a system, a designated combination of those five modules under different levels/options was made based on the

developing conditions. Once a module needs to add additional functions, the developer can simply replace the old module with a new one that is developed under the modulization standard. Such a standard has designated the interactions with other modules.

(2) To secure efficient integration, the proposed framework has to meet the requirements of the interoperability. Various communication protocols, data formats, naming conventions, and evaluation systems represent the biggest challenges of interoperating the proposed system. This study suggests that the best way to maintain interoperability is standardizing the process: to adopt a standard communication protocol instead of a vendor-proprietary protocol. To use the IFC format rather than a software-proprietary format; to follow a standard encoder rather than a company-proprietary naming convention. To refer to a standard evaluation system rather than project-proprietary evaluation.

(3) To remain the flexibility of the proposed system towards module replacement, the modulization should be standardized based on Independence Axiom. Each module should be functionally independent. To put it into another way, the DSM of the proposed system should be either a coupled matrix or a quasi-coupled matrix.

Q9: What are the functions of the proposed framework?

The overall function of the proposed system is to provide simulation-based supervisory control while automatically detecting and diagnosing operational faults. It is comprised of five modules. The functions for each module have been given as below:

(1) A1 BAS Module: To provide automatic centralized control of building facilities.

(2) A2 BDS Module: To provide a database capable of detailly describing buildings.

(3) A3 KBS Module: To solve new problems based on the solutions of similar past cases.

(4) A4 BPS Module: To simulate the building performance and provide an optimized scheme for building management.

(5) A5 FDI Module: To recognize the operational faults and pinpoint the type of fault and its location.

Q10: What functions should be adopted from the proposed framework towards promoting BIM-BMS integration at this stage?

SBSC pathway should be adopted towards integrating BIM and BMS, Wherein, BAS Module, BDS Module, BPS Module were needed.

(1) A1 BAS Module: To provide automatic centralized control of building facilities.

(2) A2 BDS Module: To provide a database capable of detailly describing buildings.

(3) A4 BPS Module: To simulate the building performance and provide an optimized scheme for building management.

Q11: What is the significance of adopting the proposed framework?

Such a framework will be used for developing a software solution in the coming research. Such a solution will be expected to improve the post-construction energy efficiency and maintenance effectiveness. Meanwhile, the proposed framework provides a pre-condition for the organizations which aims at achieving a higher BIM maturity level, especially BIM Level 3.0 and further.

Q12: How can the other functions be achieved in the future?

A knowledge base should be established for the operational faults coupled with solutions before finalizing the development of the proposed framework. Such a knowledge base will be used to develop the FFSC pathway.

10.3.4 Agile Development Findings (Q13-16)

In the agile development, a working prototype was developed. To obtain such a working prototype, a process model was established. Wherein, fours parts of work were divided. They are modeling, IoT deployment, database establishment, analysis integration. Then, a user-centralized design was made, and several end-user engagement workshops were established. Meanwhile, the development of each part was carried on separately in an agile way. The findings were responding to the investigating questions below:

Q13: Which level of SCADA should be adopted at this stage?

Considering the state-of-the-art of the proposed technologies, SCADA Level 4 was adopted in developing BIM-BMS integration in New Zealand. SCADA Level 4 refers to the IoT-Based framework. The last decade has seen a growing trend towards developing efficient IoT solutions. The rapidly increasing use of electronic products coupled with the evolution of Communication Technology (1G, 2G, 3G, 4G, 5G) provided a pre-condition of adopting IoT. On the other hand, standard protocols such as MQTT, CoAP were widely adopted among vendors. By adoption of IoT, the interoperability will be largely enhanced.

Q14: What kind of database should be used at this stage?

A relational database was sufficient to be used in storing the monitoring data while object-oriented database might be needed when the system attempts to store the entire building information in a single database. Hence, at this stage, a relational database was recommended to be used in the BIM-BMS integration in managing existing educational facilities in New Zealand.

Q15: Which graphic library can be used at this stage?

WebGL library was used for visualizing the 3D. In the past decades, the OpenGL library was frequently used in developing stand-alone 3D solutions. In spite of this, increasing the number of Internet users urgent the adoption of a web-based graphic library. In this regard, there is a trend of developing WebGL 3D engines. This library simplified the development process while brought convenience for the end users. Hence, at this time, the WebGL library was recommended to be adopted in developing web-based 3D platforms integrating BIM and BMS in New Zealand.

> Q16: How can this solution generalized to non-expert industry end users.

By adopting such a web-based 3D platform, the non-expert industry end users were expected to manage the building facilities at a higher convenience level. Comparing to the traditional information management in building O&M, where Excel is a typical tool, the O&M processes were largely simplified in the proposed system. In addition, the parts of the proposed system were developed separately. To put it into another way, when one part of it evolves, it will be easy to replace with a new part without major updates on the rest parts.

10.3.5 Pilot Testing Findings (Q17-20)

In the pilot test, the simulation results for the heating costs by using a traditional operation system, BMS, and the proposed system separately. The findings were responding to the investigating questions below:

> Q17: What is the tangible function of the proposed system that can direct to savings? And how much is it?

By adopting a BIM-BMS integration, the HVAC system was expected to save 2.20% heating costs. This saving was obtained from the accurate measurement of the indoor climates. Despite a linear relationship to the mean indoor temperature, the temperature in the terminal is over-sensitive to the HVAC operation. Traditional HVAC systems utilized terminal temperatures in their threshold settings. This inaccurate threshold controls led to a waste of electric energy use. Hence, by providing a higher accurate indoor climate measurement method, the proposed system delivered a higher energy efficiency.

Q18: What is the attribute from BMS?

In comparison with the traditional operation, BMS saved 1.52% of the heating costs. This saving was directly from the relocation of thermostats. Instead of measuring the highly sensitive terminal temperature, the temperature was measured in another position with a distance to the terminal. This temperature was demonstrated in a strong linear relationship with the mean indoor temperature. Despite this, the inhomogeneous air flow and heat exchange could reduce the accuracy. Additionally, the position of the thermostats also led to a diversity of energy efficiency.

Q19: What is the attribute from features in the proposed system rather than BMS?

In comparison to the BMS operation, the proposed system saved 0.68% of the heating costs. This saving was obtained from the thermal analysis. In BMS, an assumption of perfect mixed air was adopted. With an indoor climate adjustment from such analysis conducting in a BIM-based platform, the threshold control becomes more effective. However, the simulation was conducted theoretically, the actual savings in this regard should be further examined with a consideration of the accuracy of both the algorithm and the sensors.

Q20: How can the proposed solution generalized to the other existing buildings in New Zealand?

This study has demonstrated that the integration of BIM and BMS in the pilot case is efficient in improving the energy efficiency of the HVAC system. It is expected to reduce the electronic energy use for New Zealand educational buildings. Towards using the proposed system in another building, a specific development process should be carried on.

(1) Pathway of the system use should be identified before designing the system. As given by this study, the SBSC pathway is used for improving the operation efficiency while the FFSC pathway is reducing the maintenance costs. The organizations who intend to adopt the proposed framework should determine their purpose and choose the pathway(s) they need.

(2) Level of the technology used in each module should be designated before developing the system; this is mainly designated with consideration on both state-of-the-art for the technologies used and development budgets. Numbers of development levels were given for each module. The organization who intends to adopt the proposed framework need to choose the level for each module.

(3) The off-the-shelf components should be investigated. Using the off-the-shelf components can largely reduce the developing costs. Some of these components which are developed under our modulization standard can be directly assembled into the system. Other components with similar functions can be used after standardization of the inputs, outputs, tools, and constraints. If the proposed module component cannot be found, a specific development process should be conducted. Provided that, the modulization standard should be followed. A key thing to remember, the module should be developed separately, particularly in an agile way. This will save the development costs by providing high flexibility to change.

10.4 Synthesis of Findings

10.4.1 The Effectiveness of the Prototype in Representing the Solution

Following the proposed framework established in Chapter Eight, a working prototype was developed. Considering the maturity of New Zealand for adopting the related technologies, the working prototype merely represents the pathway of SBSC. Such pathway interacts BAS, BDS, and BPS modules.

In light of this, a process model was developed. A relational database was efficient in connection to 3D visualization in WebGL. By means of such a 3D web-based platform, the end users were efficient to manage the building facilities in a centralized control panel. Coupled with appropriate databases, the modeling process represented the BDS module. Considering the development of the SCADA framework, SCADA Level 4 was adopted. Upon the SCADA framework, the IoT process represented the BAS module. Likely, analysis integration process represented the simulation in BPS. The interactions between each process were clarified. Standardization was made by adopting standard communication protocols, data formats, naming conventions, and evaluation systems.

In view of this, the interoperability of the proposed system was maintained. Furthermore, the development of each part of the proposed system was done separately. That is to say, when one part of it updates, it will be efficient to replace with a new one without leading a major change on the rest parts. That said, the development process in an agile way remains the flexibility of our system. Thus, the working prototype was validated efficient to represent the proposed solution.

10.4.2 The Effectiveness of the Solution in Removing the Specific Barriers

Prior studies have noted the importance of BIM in the operation phase. As mentioned in the literature review, the current New Zealand FM was limited in information peculiarity and fragmentation. This gap has been validated in the focus group interview. The participants in the focus group interview explained that this was caused by the lack of intelligence in current New Zealand buildings. Provided that, a lack of data analysis was found in the current building management. Meanwhile, they suggest developing an IoT-enabled BIM-based BMS system to upgrade the current BMS-based smart buildings onto an intelligent building level. Against this background, this research set out with the aim of promoting the intelligent building in New Zealand. One of the purposes of this study was to develop an IoT-enabled BIM-based BMS application towards highly efficient building intelligence for FM. With this in mind, this research has:

(1) Developed a 3D visualized UI for presenting the BIM models.
(2) Deployed an HVAC prototype for smart control and monitoring.
(3) Integrated BIM visualized UI with facilities.
(4) Embedded an analysis application for HVAC performance.

Consequently, the findings from this study make several contributions to the current literature:

(1) This research has delivered a system that integrates BIM and BMS. As all the library or API used were open sourced, the workflow can be generalized completely to other FM applications for the same purposes.
(2) An analysis integration was made into the proposed system. The proposed BMS was expected to largely improve the building intelligence.
(3) The proposed system was applied to a New Zealand building, and the effectiveness has been evaluated. This research provides a proved benefit of using the proposed BMS, which can be used for the further validation of ROIs from the owners' perspective. This will largely accelerate the BIM adoption in New Zealand. All considered the proposed BMS was potential to solve the current gaps in New Zealand AEC/FM.

10.4.3 The Effectiveness of the Solution in Solving the Research Problem

Nowadays, the building costs in the O&M phase account for 87% of total costs for the whole lifecycle; hence, it would be effective to improve the efficiency in O&M. However, in New Zealand, the current information management process that takes place in O&M suffers from information peculiarity and fragmentation.

A typical BMS is capable of making smart monitoring and automatic control of the building facilities. By adopting it, buildings can achieve highly efficient O&M. However, as discussed in our research early, those smart buildings in New Zealand were not intelligent enough. Single BMSs might be overwhelmed by big data and fragmented information. Essentially, BIM is usually established in a building project for addressing complexity.

An integration of BIM-BMS was demonstrated in this research that enables to address above problems effectively towards highly facility intelligence. This research sets out to improve the effectiveness of BIM-BMS practices in New Zealand in the literature while reveals the realities in the industry.

Prior to commencing this research, a literature review was conducted to identify the investigating questions. In the literature, no empirical evidence has been validated in New Zealand and BIM application in facility management has been identified as a bottleneck in the AEC/FM industry.

To avoid the conflicts of interest, this research conducts a focus group interview recruiting panellists from different New Zealand companies in the related field. One panellist can raise a question at any time on the others' responses. Consequently, they might be unanimous in one view or disputes still exist on that question. The panel provides an overview of the BIM adoption in New Zealand and discusses barriers for BIM use in facility management paired with potential solutions. The following findings were obtained from the qualitative phase: currently, BIM in New Zealand is still early while BMS has been used for years; nevertheless, no BIM-BMS integration has been made in New Zealand; not to mention the well-recognized big data issues, current BMS in New Zealand was mainly limited with a lack of intelligence; to achieve an intelligent BMS, BIM is a pre-condition; however, the immature organizational readiness in New Zealand industry becomes the roadblock of current BIM-BMS practices.

In view of this, this study designed a solution and provided empirical data for adopting BIM in building O&M phase. An evaluation process was made for adopting a BIM-BMS integration in the selected pilot case. The results of the testing suggested that, by adopting the proposed system, the efficiency of the information management process for building facilities was largely improved.

10.5 Relating the Findings to the Research Literature

This study set out with the aim of investigating the effectiveness of BIM-BMS integration in managing existing educational building facilities in New Zealand. Numbers of outcomes have been delivered including a framework, a working prototype, and a pilot case study. The purpose of this section was to compare these outcomes with the others' research from the wide literature.

10.5.1 Testing Results Obtained by Other Researchers

A pilot case was tested in this study for evaluating the energy efficiency by adopting BMS and BIM-BMS integration separately. The results were obtained from an educational building that BMS is expected to save 1.52% whereas BIM-BMS integration can attribute a further 0.68% (totally 2.20%). This 1.52% from BMS were mainly from the improvement of the automation. This finding is consistent with that of Habibi (2017) who found that appropriate 1% energy costs can be saved from the adoption of BMS in the educational building. On the other hand, with the help of the optimization from engaging BIM, a further 0.68% can be saved. This study supports evidence from previous observations (Granderson, Lin, Singla, Fernandes, & Touzani, 2018) that the energy consumption can be reduced by 1.9% with an optimized BMS. Interestingly, research also delivered a 40% saving on energy use by using CO_2 sensors (Aste, Manfren, & Marenzi, 2017). That is because the CO_2 sensors are more efficient in measuring the occupant behaviors. When no one in the room, the HVAC will be closed even the indoor environments are not comfortable. This has emphasized a further optimization of sensor deployment in the future FM research. Besides, the FFSC, which is not tested by this study at this stage, was found to save up to 30% for office buildings and 50% for industrial buildings. Additionally, with lifecycle management, the operation in office buildings was expected to have an up to 50% saving on energy use (Eleftheriadis, Mumovic, & Greening, 2017). The testing results from other researchers have been listed in Table 31.

Table 31 a List of Testing Results Obtained by Other Researchers.

Measures	**Effectiveness**	**Type (Countries)**
SBSC	Saved 1% of the energy consumption in both heating and cooling (Habibi, 2017). (Attributes from Automation)	Educational buildings (Italy)
	Saved 1.9% of the energy consumption in both heating and cooling (Attributes from both Automation and Optimization) (Granderson et al., 2018).	Educational buildings (USA)
	Saved 40% and 20% of the energy consumption in heating and cooling separately (measured by CO2 sensors) (Aste et al., 2017)	Commercial buildings (Italy)
FFSC	Saved 5–30% of the energy consumption (Dong et al., 2014).	Office buildings (USA)
	Saved up to 50% energy savings (Gourlis & Kovacic, 2017).	Industrial buildings (Austria)
LCA	Saved up to 0.4GJ/m^2 of lifecycle energy savings (Shadram & Mukkavaara, 2018).	Educational buildings (Sweden)
	Saved up to 20% of the energy consumption (Eleftheriadis et al., 2017).	Office buildings (UK)

10.5.2 Prototypes Developed by Other Researchers

A working prototype was developed for representing the SBSC pathway of the proposed system. The outcomes include a process model covering four steps: Modelling, IoT, Database, and Simulation. Processes developed on BIM platforms were identified as similar prototypes (See Table 32). These process models were mainly divided into numbers of parts by functional tasks. Smart-BIM virtual prototype (Heidari et al., 2014) contains several managers, and each represents a specific task. Despite this, multiple managers might be developed by or interoperated with the same technologies or platforms or APIs where they can be grouped together. On the other hand, BIM-R platform (Scherer & Katranuschkov, 2018) provided a layer-based division on the process. Parts wherein might cover more than one module.

Table 32 a List of Prototypes Developed by Other Researchers.

Name	**Functions**	**Processes**
Smart-BIM virtual prototype (Heidari et al., 2014).	To design and represent real usage of space by creating a virtual environment which can interact with users.	Main Menu manager; Camera Manager; Narrator Manager; Lighting Manager; Timeout Manager; Smart Kitchen Table Manager.
A BIM-based tool (Nizam, Zhang, & Tian, 2018).	To assess embodied energy for the whole life cycle of a building construction project	Data Collection; Data Mapping; Data Analysis.
BIMification (Scherer & Katranuschkov, 2018).	To combine holistically BIM-based design and performance analysis.	Anamnesis; Diagnosis; Therapy.
BIM-R platform (Scherer & Katranuschkov, 2018).	To perform analyses and calculations based on specified rules in regulations or standards.	Presentation Layer (3D Viewer, Parser, UI); Application Layer (Format converter, Reasoning, and Query Wrapper); Storage Layer (Data sources).
Scan-to-BIM (Adán, Quintana, Prieto, & Bosché, 2018).	To recognize and reconstruct building objects from 3D scanning.	Previous Stages: Data Acquisition, Data Segmentation, Segments of Structural Components, Wall Segments; Data Preparation: Raw orthoimages Extraction, Highlight Zones Restoration, Restored Orthoimages,

		Separation of Geometric and Colour Components; Recognition and Positioning: Recognition of structural parts in the wall, Recognition of Secondary Building Components.

Rather than either independent or oversimplified, our process model was divided by two constraints: (1) only one module should be cover by one part; (2) parts developed by the same technology (discipline) should be grouped together in one module. By the first constraint, the process was divided into a BAS process, a BDS process, and a BPS process. In the BDS process, two technology were found: modeling and database. Hence, the process model was determined as modeling & database (BDS), IoT (BAS), and Analysis (BPS). Additionally, the process model of BIM specification can be used for the future development of the FFSC pathway.

Table 33 a List of Frameworks Established by Other Researchers.

Name	Functions	Modulization
7D BIM development framework (McArthur, 2015).	To offer a consolidated interface for information regarding all aspects of building operational performance.	Data analysis and collection; Needs analysis; Rich Room Data Schedule Update; Systems and Site Data Collection; BIM Model Update; Demonstrate, Evaluate and Review.
An integrated BIM-based framework (Shadram & Mukkavaara, 2018).	To support the making of appropriate design decisions by solving the trade-off problem between embodied and operational energy.	BIM Module; Data Repository Module; Energy Performance Simulation Module; Multi-Objective Optimization Module.
A BIM-based framework (Marzouk & Abdelaty, 2014a).	To monitor indoor temperature and particulate matter concentration levels.	Monitoring indoor environmental quality; BIM-Based Model; Subway Maintenance Ranking System.
BPOpt (Rahmani Asl, Zarrinmehr,	To optimize the building performance.	BIM; BPS;

Bergin, & Yan, 2015).		BIM-Based Performance Optimization; Multi-Objective Optimization Tool.
Ontology-based framework under BIM environment (Zhong, Gan, Luo, & Xing, 2018).	To conduct building environmental monitoring and compliance checking.	Ontology Development; Building Environmental Compliance Checking.
Holistic BIM framework for sustainable low carbon design of high-rise Buildings (Gan et al., 2018).	To enhance the sustainable low carbon design of high-rise buildings.	Creation of BIM Model; Embodied Carbon Quantification; Operational Carbon Quantification; Scenario Study and Identification for Design Improvement.
An integrated BIM-FM methodology framework (W. Chen, Chen, Cheng, Wang, & Gan, 2018).	To conduct automatic scheduling of facility maintenance work orders.	As-Built Model Preparation and Data Integration; Identification of Failure Components to be Maintained; The BIM-Based Sub-Optimal Maintenance Path Planning; BIM-Based Automatic Facility Maintenance Work Order Scheduling.
A BIM-based framework to support safe facility management processes (Wetzel & Thabet, 2015).	To store, retrieve, and manage task specific safety information.	Relevant Safety Data Collection & Classification; Data Engine; Safety Protocol Output to User.

10.5.3 Frameworks Established by Other Researchers

A framework was designed by this study for conducting simulation-based supervisory control while automatically detecting and diagnosing operational faults. Frameworks for promoting BIM in building O&M were identified as similar solutions (Table 33). Among them, the first five frameworks were developed to facilitate the energy efficiency by providing building performance simulation and optimization (McArthur, 2015). While the sixth one adopting an LCA method with the same purpose. Then, the seventh framework focuses on the maintenance scheduling. The last one was developed to conduct safety information management.

As shown in the first six frameworks, all of them adopted an individual BIM model. However, there are still some other modules that depend on BIM, such as BIM-Based Performance Optimization in BPOpt (Rahmani Asl et al., 2015). To avoid of the functional dependence, our framework was designed with a BDS that assisted with BIM tools towards maintaining information models. As shown in the first five frameworks, BIM is also assisted with the simulation and the monitoring data. To be consistent with these frameworks, our framework was given an individual BAS module for storing monitoring data and a BPS module for conduct simulation and analysis. Wherein, the performance optimization was included in our BPS module whereas other researchers made them into two separate modules. Hence, compared to the frameworks established by other researchers, our framework performs the highest functional independence. Such independence then leads to a highly flexible solution.

10.6 Summary

This chapter presented the synthesis and discussion of the results and findings of this study. To begin with, the nature of the problem was restated. Then, the effectiveness of BIM-BMS on reducing the energy consumption, removing the New Zealand specific barriers, and solving the research problem was discussed by combining all the research findings. This provided a concluding remark for the next chapter. Finally, this chapter generalized the research findings to the wide literature. Comparisons to testing results, prototypes, and frameworks by delivered other researchers were made. This distinguishes the originality of our findings. In the next chapter, conclusions of this research will be given.

Chapter 11 Conclusions

11.1 Introduction

The purpose of this study is to investigate the effectiveness of BIM-BMS integration in managing existing educational facilities in New Zealand. To begin with, this chapter summarises the challenges faced prior to commencing this study and how they were addressed. It then reflects on the objectives set for this study including how these objectives have been achieved. It highlights the original contributions to theory and practice made by this study. A list of recommendations is given to enable adoption of the BIM-BMS integration. Also, the limitations of this research are provided. Finally, the chapter states the concluding statement to end up this study.

11.2 Challenges

To conduct an exploratory study, a range of relatively well-defined terminologies, a series of existing empirical data to compare with, and an objective evaluation method are essential. However, these pre-conditions cannot be achieved. In this regard, three main challenges were found:

(1) Lack of specific terminology in New Zealand

The current terminologies and concepts cannot be adapted into the New Zealand context. In the past, New Zealand often looked into the terminologies from the UK and Australia for guidance and adopted their strategies accordingly. However, in BIM subject field, such terminology may not work, as the underlying dynamics of the UK and Australian AEC/FM industries are different from the New Zealand one. This arose a challenge to this study. Adopting an inaccurate terminology will cause a significant decrease in the quality of the research outcomes. Facing this issue, this study defined a New Zealand specific terminology prior to commencing this research.

(2) Lack of evaluation method in building performance in New Zealand

Presently no evaluation method was confirmed to be effective in measuring the benefits of BIM in building O&M phase. This issue made the evaluation process become more difficult. In this regard, we designed an evaluation process by simulating and comparing the energy costs in different operational modes.

(3) Lack of empirical data in New Zealand

In recent, no empirical data on the use of BIM-BMS integration in New Zealand. To generalize this outcome, we compared the evaluation results to the similar testing data from the wide literature. Such similar tests represented the operational data with similar functional delivery from system optimization. In our system, BIM was used for analyzing the operational data to optimize the supervisory control. In terms of this, we compare our results to the energy savings from other research which optimize the supervisory control by analyzing the operational data.

11.3 Restatement of the Research Aim and Objectives

Given the literature, the research problem was identified as the weak information management process in building facilities O&M phase. Towards this problem, a solution of proposing BIM-BMS integration was proposed from the literature. Despite this, the lack of empirical data was found to demonstrate effective for this solution. In this regard, the research aims to investigate the effectiveness of BIM-BMS integration in managing existing educational building facilities in New Zealand. Since the problem is complex, this study put a lens of complexity theory and conducted a mixed methods research to explore the research problem. Towards achieving the research aim, five objectives were attained in five stages separately.

11.3.1 Objective 1

To refine the New Zealand specific BIM and its related terminologies.

New Zealand terminologies for BIM and its related concepts was provided at this stage. These terminologies are expected to become the base of all BIM research in New Zealand. The following conclusions were drawn in response to Objective 1:

(1) The results of this study indicate that traditional BIM related definitions cannot be used in New Zealand context. Importantly, this study has raised important questions about the nature of BIM. Traditional definitions cannot meet the requirements above BIM Level 3.0. As there is a need to integrate monitoring data in the BIM model, a new BIM definition involves analogical data beyond the digital representation. Hence, BIM was defined as a process of creating, sharing, exchanging, integrating, and managing digital and analogical representations with multiple dimensions, in multiple disciplines, by multiple stakeholders, at multiple lifecycles, for multiple projects.

(2) The findings of this study suggest that traditional BIM maturity levels were not adaptive in today's New Zealand context. From a New Zealand perspective, this study provided a specific BIM maturity definition as followings: BIM Level 0.0: Outputs in the same discipline are made separately, and once one changes, the corresponding outputs cannot be updated automatically. BIM Level 1.0: Outputs in the same discipline are responsive to each other, and there are no gaps within one discipline. However, gaps exist among different disciplines. BIM Level 2.0: People in one team can federate multi-dimensional works in all disciplines together. BIM Level 3.0: People from all stakeholders are able to collaborate all discipline works in a multi-dimensional repository throughout the whole lifecycle. BIM Level 4.0: BIMs from multiple projects are interconnected, which enables the interaction in knowledge, spatial, economic, society, industry, etc.

(3) The evidence from this study suggests that traditional barriers to BIM adoption are not suitable to be used in a New Zealand context. In light of this, this study has identified the barriers dynamically for each BIM maturity level in a New Zealand context: BIM Level 0.0 barriers: lack of software and individual demand. BIM Level 1.0 barriers: lack of cooperation and organizational demand. BIM Level 2.0 barriers: lack of expertise and client demand. BIM Level 3.0 barriers: lack of legal policy and government demand. Last, this research has distinguished the terms such as BIM 4.0, smart city, CIM and the disputes in BIM dimensions and lifecycle phases are well-addressed.

11.3.2 Objective 2

To identify the current barriers to adopting BIM-BMS integration for managing existing educational facilities in New Zealand.

The New Zealand specific barriers to BIM adoption were identified at this stage. This finding from the qualitative research was then examined in the quantitative phase. The following conclusions can be drawn in response to Objective 2:

(1) The results of this study indicate that the BIM adoption was low in operation phase in New Zealand.

(2) The findings of this study suggest that there was no empirical data on operational BIM use in New Zealand.

(3) The data suggest that the majority of current HVAC systems in New Zealand educational buildings were not energy efficient.

(4) The findings of this study suggest that the majority of BMS-based HVAC systems adopted in New Zealand educational buildings were not intelligent enough.

11.3.3 Objective 3

To design a functional framework towards a BIM-BMS integration for managing existing educational facilities in New Zealand.

A functional framework that is efficient in integrating BIM and BMS was delivered at this stage. The following conclusions can be drawn in response to Objective 3:

(1) This study has shown that the overall function of the proposed system is to provide simulation-based supervisory control while automatically detecting and diagnosing operational faults. It is comprised of five modules. The functions for each module have been given as below: A1 BAS Module: To provide automatic centralized control of building facilities. A2 BPS Module: To provide a database capable of detailly describing buildings. A3 KBS Module: To solve new problems based on the solutions of similar past cases. A4 BPS Module: To simulate the building performance and provide an optimized scheme for building management. A5 FDI Module: To recognize the operational faults and pinpoint the type of fault and its location.

(2) The results of this design show that the proposed framework presents high flexibility. Modulization of the proposed system is standardized based on Independence Axiom. Each module is functionally independent. This remains the flexibility of the proposed system towards module replacement.

(3) The research has also shown that the proposed framework presents high interoperability. This study standardizes the implementing process to maintain the interoperability by adopting a standard communication protocol instead of a vendor-proprietary protocol. Using the IFC format rather than a software-proprietary format. Following a standard encoder rather than a company-proprietary naming convention. Referring to a standard evaluation system rather than project-proprietary evaluation.

11.3.4 Objective 4

To develop a working prototype for managing existing educational facilities in New Zealand.

The main goal of the current study was to develop a prototype (both software and hardware) under the framework established before. This prototype will be tested in the next stage. The following conclusions can be drawn in response to Objective 4:

(1) This study has identified the process model of our system as modeling & database (BDS), IoT (BAS), and Analysis (BPS). Rather than either independent or oversimplified, our process model was divided by two constraints: (a) only one module should be covered by one part; (b) parts developed by the same technology (discipline) should be grouped together in one module. By the first constraint, the process was divided into a BAS process, a BDS process, and a BPS process. In the BDS process, two technologies were found: modeling and database.

(2) This study has identified the current application levels of the proposed system in New Zealand. Considering state-of-the-art of the proposed technologies, SCADA Level 4 was adopted in developing BIM-BMS integration in New Zealand. While a relational database was sufficient to be used in storing the monitoring data while object-oriented database might be needed when the system attempts to store the entire building information in a single database. Meanwhile, WebGL library was used for visualizing the 3D. All things considered, by adopting such a platform, the non-expert industry end users were expected to manage the building facilities at a higher convenience level.

(3) This study has shown that the parts of the proposed system were developed separately. To put it into another way, when one part of it evolves, it will be easy to replace with a new part without major updates on the rest parts.

11.3.5 Objective 5

To evaluate the energy savings from a BIM-BMS integration on managing existing educational facilities in New Zealand

The energy savings from the proposed system was evaluated at this stage. This result was consistent with similar results from the wide literature. The following conclusions can be drawn in response to Objective 5:

(1) This study has found that generally the BIM-BMS integration was expected to save 2.20% of the heating costs upon the traditional HVAC operation. This saving was obtained from the accurate measurement of the indoor climates. Traditional HVAC systems utilized terminal temperatures in their threshold settings. In spite of a linear relationship to the mean indoor temperature, the temperature in the terminal is over-sensitive to the HVAC operation. By measuring such inaccurate temperature, the controllers are led to a waste of electric energy use. Thus, by providing a higher accurate indoor climate measurement method, the proposed system delivered a higher energy efficiency.

(2) This study has shown that BMS saved 1.52% of the heating costs upon the traditional operation. This saving was directly from the relocation of thermostats. Instead of measuring the highly sensitive terminal temperature, the temperature was measured in another position with a distance to the terminal. This temperature was demonstrated in a strong linear relationship with the mean indoor temperature. Despite this, the inhomogeneous air flow and heat exchange could reduce accuracy. Additionally, the position of the thermostats also led to a diversity of energy efficiency.

(3) This study has also found that the BIM-BMS integration saved 0.68% of the heating costs upon the BMS alone. This saving was obtained from the thermal analysis. In BMS, an assumption of perfect mixed air was adopted. With an indoor climate adjustment from such analysis conducting in a BIM-based platform, the threshold control becomes more effective.

(4) This study has demonstrated that the integration of BIM and BMS in the pilot case is efficient in improving the energy efficiency of the HVAC system. It is expected to reduce the electronic energy use for New Zealand educational buildings. Towards using the proposed system in another building, a specific development process should be carried on: in the first place, the pathway of the system use should be identified before designing the system. Second, the level of the technology used in each module should be designated before developing the system. Third, the off-the-shelf components should be investigated.

11.4 Contributions to Theory and Practice

The subject matter of this study aligns with two main priority areas identified in the Building a Better New Zealand strategy (BRANZ, 2014): sustainability (more efficient buildings); and automation, industrialisation and new technologies (advancing building information modeling). In response, this study investigated the effectiveness of using advancing building information modeling towards gaining more efficient buildings. There are several important areas where this study makes an original contribution to the New Zealand building sector:

(1) This is the first study to define the BIM and its related terms from a New Zealand perspective. Various BIM definitions exist for decades whereas most of these definitions were made by organizations from USA and UK. Provided that, larger native markets, such as in the USA, are BIM incubators in nature. Then again, government policies also contribute to the BIM adoption. That said, countries such as the UK mandated BIM which led to a higher proportion of BIM adoption. Altogether, different context will bring different measurement for BIM maturity. Proposing a technology without a proper definition might cause trouble. To put it in another way, having New Zealand oriented BIM and its related definitions are

the pre-condition for promoting BIM in New Zealand. Towards this end, this study reformed the definitions for BIM, BIM maturity, BIM dimensions, and so on while these results can be generalized into other BIM research and applications in New Zealand.

(2) This study provides new insights into the BIM adoption in each maturity level in New Zealand and provided the solutions corresponded. In the literature, numbers of research discussed the barriers to BIM adoption. However, the barriers identified were inflexible. That is to say, all the possible barriers were analyzed equally. This will confuse the BIM end users in New Zealand that barriers vary in different maturity levels and contexts. Particularly, the barriers to BIM adoption in New Zealand are different from the ones in other counties. While the contemporary issues for BIM adoption in New Zealand are different from the ones when New Zealand BIM achieve a higher maturity level. Hence, the findings of this study make an important contribution to the strategy of BIM adoption in the different period. Besides, this research has largely eliminated the impact of the research bias in evaluating New Zealand BIM and BMS adoption. The adoption rates have been revaluated in the focus group. The participants compared these rates with what they perceived. A new doubt was raised that "can BIM adoption rate tell a condition for BIM practices?" Essentially, the findings contribute to the New Zealand industry by indicating that the current assessment criteria for BIM adoption should be further developed to avoid this conflict.

(3) This research has identified the relationship between BIM and BMS from both micro and macro BIM for the first time. Significantly, the findings will be of interest to respond to the call for new thinking about the contributions from BIM (beyond the function of BMS) in facilitating building O&M. Besides, this research has clearly distinguished smart building and IB. The lack of intelligence has been

identified as one of the limitations of current BMSs from the industry perspective. While BIM has been identified as the pre-condition for promoting the intelligence of BMS. This finding contributes to answering the question, “What are the benefits of going the extra mile (and cost) to operate and maintain a fully integrated BIM model?”

(4) This is the first study to establish a conceptual framework for nD BIM-IKBMS. Prior to commencing this study, nD BIM-IKBMS was first coined by GhaffarianHoseini et al. (2014) in an extended abstract. The significance of it has been demonstrated in a review article by GhaffarianHoseini, Zhang, et al. (2017). As has been proved, ND BIM-IKBMS was efficient for improving the effectiveness of building information management. It gives a big picture of the advanced building information management for existing buildings. It is expected that this research will contribute to a deeper understanding of applying BIM in the post-construction phase.

(5) This study provided a New Zealand existing educational building pilot case paired with its evaluation for the energy savings by using the proposed solution. As mentioned before, there was less empirical data for BIM practices in New Zealand whereas flash ship projects which claim the use of BIM were not well evaluated. Such pilot test presented here provides one of the earliest investigations into evaluating how effective the BIM-BMS integration is on managing existing building facilities in New Zealand. Meanwhile, BIM empirical data from O&M phase will be contributed to the wide literature.

11.5 Implications

The results of this study have implications for potential positive social change on the individual level, organizational level, at the national level, as well as the international level.

At the individual level, the results of this study may inform the individuals from the construction stakeholders on expanding their knowledge on BIM use in building O&M phase.

At the organizational level, the results of this study have implications for reducing the costs for the companies by improving the efficiency of their workload and energy use. The results of this study indicate that approaching the problem using nD BIM-IKBMS is beneficial to solving the problem in managing educational facilities in New Zealand. The benefits in this level can be summarized as below:

(1) The reduced costs from improved management of the building can be realized directly by the building owner or flow through to the owner by way of increased rent when compared with less efficient, but otherwise comparable buildings.

(2) Reduce the maintenance response time for facility errors for remaining the facility accessibility for the occupants.

(3) Achieve more efficient use of staff from the monitoring and intelligently management and control of energy services in buildings by maintaining a balance between conditions, energy use, and operating requirements.

(4) The improved comfort level for occupants from personalizing climate by real-time monitoring and smart control and extending the life of maintenance systems by providing a complete understanding of energy consumption by enabling preventive and predictive maintenance, fault finding and automated control.

Besides, the results of this study might also have implications at the national level. Our study provided a solid research base for exploring BIM in New Zealand. The results of this study also have empirical implications. A pilot case study in New Zealand was provided for the future applications. Meanwhile, the results of this study will inform policymakers in ways that will produce national BIM guidelines or standards in New Zealand.

Additional implications relate to the international generalization of our study. With a comparison to the researches all over the world, our outcomes might be applied to other counties. In the first place, the terminologies were developed based on a context with a slower developing speed in BIM related technology. Despite this, such terminologies might not be able to apply in the UK, or any other countries who mandated BIM into a high developing speed. As for the framework established by this study, it might be generalized to a global context. Despite, it should be future demonstrated in this regard. Additionally, the empirical data can be referred by the BIM users in other countries.

The outcome of this study can be applied in New Zealand building sector. It is feasible to deploy the proposed system in an educational building in New Zealand. However, the energy savings should be re-evaluated. The main barrier of adopting the proposed system in New Zealand is the policy of promoting BIM. Most of the buildings do not have a BIM model, which largely in crease the initial costs of adopting the proposed system.

11.5.1 Uniqueness of the Research

The solution developed in this study is unique to the New Zealand AEC/FM industry for several reasons.

(1) It was developed from a focus group interview with the New Zealand-based FM experts with more than 25 years of experience. The responses received from these experts have ensured that the framework is applicable to New Zealand's situation in relation to educational facilities management.

(2) Empirical studies of the use of BIM in the O&M phase have not been previously undertaken in New Zealand. A number of previous researches have indicated the potential benefits of BIM in the O&M phase. However, no studies have expressly

evaluated the tangible benefits of BIM in the O&M phase in a quantitative way. This is the knowledge gap in New Zealand AEC/FM that needs to be filled urgently, and it is also one of the objectives reported in this thesis. Towards this end, this study is the first of its kind in New Zealand to investigate the effectiveness of BIM-BMS integration in managing existing educational facilities.

(3) The framework was designed to be flexible and applicable to the various situation in New Zealand existing buildings, especially educational buildings. To verify its flexibility, the framework was a test based on the Independence Axiom. Coupled with two working pathways, the proposed framework was confirmed of functional independence. This has ensured the applicability of our framework in the New Zealand's context in relation to educational facilities management. Besides, considering the development of the technology in New Zealand AEC/FM industry, a specific pathway of SBSC was given to be used at this stage. Whereas an FFSC pathway was left to be developed in the next level of technology adoption.

11.5.2 Generalization of the Research

This study set out with the aim of investigating the effectiveness of BIM-BMS integration in managing existing educational building facilities in New Zealand. Numbers of outcomes have been delivered, including a functional framework, a working prototype (or a process model), and a pilot case study. These outcomes can be generalized into a wider context.

(1) The proposed framework was compared to those all over the world who promote BIM in building O&M. The evidence from this study suggests that our framework performs the highest functional independence comparing to the frameworks established by other researchers. Such independence then leads to a highly flexible solution. Meanwhile, the interoperability has been promoted by standardization.

Such a standardization process was expected to facilitate the generalization of the proposed framework into other countries.

(2) In the pilot case study, the energy savings for BIM-BMS integration and BMS alone were obtained separately from an educational building in New Zealand. This finding is consistent with that of an educational building test in Italy and another test in a USA educational building. In general, therefore, it seems that the testing results in our study were not largely dependent on contexts. The only independent variables for generalizing into a wider context seem to be the outdoor temperature. Thus, it is expected to be generalized into contexts with similar outdoor temperature.

(3) In the development, the process model was divided into several parts. These parts were developed separately in an agile way. These parts of the system can be reused from one project to another. Hence, the working prototype can be reused into a global context.

11.6 Limitations

There are certain limitations to the current study. Despite this, we believe our work could be a springboard for the use of BIM in O&M in New Zealand. The limitations are listed below:

(1) The most important limitation lies in the contexts of the findings being generated. The present study has only investigated the effectiveness of the solution in New Zealand. As discussed to the wide literature, all the findings might be able to be generalized to other countries. However, they were merely validated in the New Zealand context. A specific validation process will be needed once applied in other counties.

(2) The present study has only investigated the effectiveness of BIM-BMS integration. Other solutions which might also promote the building sustainable performance were not considered in this study.

(3) The current study was not specifically designed to quantitatively validate the other benefits of adopting our system except energy efficiency. Considering the research budgets, other benefits were merely demonstrated by the evidence from the literature.

(4) The present study has only investigated the effectiveness of SBSC pathway of our system which integrates BIM and BMS. Due to a lack of resources in the current New Zealand AEC/FM industry, FFSC was left for future development once suitable.

(5) The present study has investigated the effectiveness of BIM-BMS integration in an educational building pilot case. Other types of building were not tested. As found in the literature, the energy savings from a specific tool might vary largely from building types. Despite this, the qualitative findings, including the framework and the process model, can still be efficiently applied to them.

(6) This study explores the barriers to BIM-BMS integration and then provides a technical solution to remove these barriers. Technical solutions are limited in resolving adoption and implementation problems. Major issues with the adoption of any innovative system come from people and their resistance to change. These issues have been excluded from this study.

11.7 Future Directions

Based on the limitations of the current study, the following recommendations are made for the consideration of future study related to this subject area.

11.7.1 Generalizations

It is recommended to generalize our results into another project. Provided that, a specific development process should be carried on: first of all, the pathway of the system use should be identified before designing the system. Then, level of the technology used in each module should be designated before developing the system. Last, the off-the-shelf components should be investigated.

Nevertheless, such projects will vary by the country, building type, building system, evaluation method. The effectiveness of the proposed system in generalizing to another context should be investigated.

In the future study, more BIM-based analysis functions in all building systems will be developed, and then examined. Then again, there were numbers of other systems in the building which was not validated by this research. A focus on developing applications for the other building systems was recommended, especially the second large energy attribute – lighting system.

11.7.2 Complements

Further work needs to be done to develop the FFSC pathway. A knowledge base should be established for the operational faults coupled with solutions before finalizing the development of the proposed framework. Such a knowledge base will be used to develop the FFSC pathway. As mentioned before, the use of FFSC will be expected to save up to 50% energy costs.

11.7.3 Optimizations

This study has raised a design scheme for the nD BIM-IKBMS framework. Such a design scheme has been verified by Independence Axiom. Despite this, it is still not the best scheme. Further optimizations should be made. The optimized scheme should be evaluated by using information axiom. Once the information content of the optimized design smaller than the original one, while retaining the functional independence, it is suggested to be considered for replacement.

11.8 Concluding Statements

This study has explored the solutions for improving the current building information management process. An integration of BIM and BMS was identified as the solution of this research. Whereby, this study aims to investigate the effectiveness of the BIM-BMS integration. To begin with, this study has found that the existing definitions for BIM related terminologies cannot be adapted into a New Zealand context. To form a base for BIM research, this study refined these terminologies; this study has shown that the current New Zealand BIM adoption was still early whereas the majority of existing BMSs here were not intelligent enough to maintain the energy efficiency; the results of this investigation show that the solution is flexible and capable to be applied to New Zealand's situation in relation to educational facilities management; the pilot test confirmed that BMS saved 1.52% heating costs in a New Zealand educational building whereas BIM-BMS integration attributed a further 0.68% (totally 2.20%).

Finally, it is hoped that the findings of this research study contribute to the existing body of knowledge and help promote the use of BIM-BMS integration in managing New Zealand building facilities.

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Appendix A: Ethics Approval Letter

AUTEC Secretariat

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22 November 2017

Ali GhaffarianHoseini
Faculty of Design and Creative Technologies

Dear Ali

Re Ethics Application: **17/384 Investigating the effectiveness of building information model integrated building management system on managing existing educational building facilities in New Zealand**

Thank you for providing evidence as requested, which satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC).

Your ethics application has been approved for three years until 22 November 2020.

Standard Conditions of Approval

1. A progress report is due annually on the anniversary of the approval date, using form EA2, which is available online through http://www.aut.ac.nz/researchethics.
2. A final report is due at the expiration of the approval period, or, upon completion of project, using form EA3, which is available online through http://www.aut.ac.nz/researchethics.
3. Any amendments to the project must be approved by AUTEC prior to being implemented. Amendments can be requested using the EA2 form: http://www.aut.ac.nz/researchethics.
4. Any serious or unexpected adverse events must be reported to AUTEC Secretariat as a matter of priority.
5. Any unforeseen events that might affect continued ethical acceptability of the project should also be reported to the AUTEC Secretariat as a matter of priority.

Please quote the application number and title on all future correspondence related to this project.

AUTEC grants ethical approval only. If you require management approval for access for your research from another institution or organisation then you are responsible for obtaining it. You are reminded that it is your responsibility to ensure that the spelling and grammar of documents being provided to participants or external organisations is of a high standard.

For any enquiries, please contact ethics@aut.ac.nz

Yours sincerely,

Kate O'Connor
Executive Manager
Auckland University of Technology Ethics Committee

Cc: tongrui.zhang@aut.ac.nz; Nicola Naismith; John Tookey

Appendix B: Signatures for Consent Form

Consent Form

Project title: ***Investigating the effectiveness of BIM-BMS Integration on Managing Existing Educational Building Facilities in New Zealand***

Project Supervisor: ***Dr Ali GhaffarianHoseini, Dr Nicola Naismith, and Prof John Tookey***

Researcher: ***Tongrui ZHANG***

- ✓ I have read and understood the information provided about this research project in the Information Sheet dated 29/10/2017.
- ✓ I have had an opportunity to ask questions and to have them answered.
- ✓ I understand that my name, position and affiliation will be disclosed in the publications and thesis for academic purpose.
- ✓ I understand that notes will be taken during the focus group and that it will also be audio-taped and transcribed.
- ✓ I understand that taking part in this study is voluntary (my choice) and that I may withdraw from the study at any time without being disadvantaged in any way.
- ✓ I understand that if I withdraw from the study then, while it may not be possible to destroy all records of the focus group discussion of which I was part, I will be offered the choice between having any data that is identifiable as belonging to me removed or allowing it to continue to be used. However, once the findings have been produced, removal of my data may not be possible.
- ✓ I agree to take part in this research.
- ✓ I wish to receive a summary of the research findings (please tick one): Yes✓ No○

Participant's signature: ....

Participant's name: Michael Welzel

Participant's Contact Details (if appropriate):

....

....

....

....

Date:

Approved by the Auckland University of Technology Ethics Committee on 20/11/2017 AUTEC Reference number 17/384.

Note: The Participant should retain a copy of this form.

Consent Form

Project title: ***Investigating the effectiveness of BIM-BMS Integration on Managing Existing Educational Building Facilities in New Zealand***

Project Supervisor: ***Dr Ali GhaffarianHoseini, Dr Nicola Naismith, and Prof John Tookey***

Researcher: ***Tongrui ZHANG***

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- ✓ I agree to take part in this research.
- ✓ I wish to receive a summary of the research findings (please tick one): Yes✓ No○

Participant's signature: ....[signature]..........

Participant's name: ....DAVID LANG..........

Participant's Contact Details (if appropriate):

..........N/A..........

....

....

....

Date: 06 DEC 17

Approved by the Auckland University of Technology Ethics Committee on 20/11/2017 AUTEC Reference number 17/384.

Note: The Participant should retain a copy of this form.

Consent Form

Project title: ***Investigating the effectiveness of BIM-BMS Integration on Managing Existing Educational Building Facilities in New Zealand***

Project Supervisor: ***Dr Ali GhaffarianHoseini, Dr Nicola Naismith, and Prof John Tookey***

Researcher: ***Tongrui ZHANG***

- O I have read and understood the information provided about this research project in the Information Sheet dated 29/10/2017.
- O I have had an opportunity to ask questions and to have them answered.
- O I understand that my name, position and affiliation will be disclosed in the publications and thesis for academic purpose.
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- O I agree to take part in this research.
- O I wish to receive a summary of the research findings (please tick one): YesO NoO

Participant's signature: ....

Participant's name: IAN JACKSON

Participant's Contact Details (if appropriate):

Level 1
28 Customs Street East
AuckLAND
027 2963324 ian.jackson@zuuse.com.

Date:

Approved by the Auckland University of Technology Ethics Committee on 20/11/2017 AUTEC Reference number 17/384.

Note: The Participant should retain a copy of this form.

Consent Form

Project title: ***Investigating the effectiveness of BIM-BMS Integration on Managing Existing Educational Building Facilities in New Zealand***

Project Supervisor: ***Dr Ali GhaffarianHoseini, Dr Nicola Naismith, and Prof John Tookey***

Researcher: ***Tongrui ZHANG***

- [x] I have read and understood the information provided about this research project in the Information Sheet dated 29/10/2017.
- [x] I have had an opportunity to ask questions and to have them answered.
- [x] I understand that my name, position and affiliation will be disclosed in the publications and thesis for academic purpose.
- [x] I understand that notes will be taken during the focus group and that it will also be audio-taped and transcribed.
- [x] I understand that taking part in this study is voluntary (my choice) and that I may withdraw from the study at any time without being disadvantaged in any way.
- [x] I understand that if I withdraw from the study then, while it may not be possible to destroy all records of the focus group discussion of which I was part, I will be offered the choice between having any data that is identifiable as belonging to me removed or allowing it to continue to be used. However, once the findings have been produced, removal of my data may not be possible.
- [x] I agree to take part in this research.
- [x] I wish to receive a summary of the research findings (please tick one): Yes [x] No ○

Participant's signature: [signature]

Participant's name: JACK CRUYTZEN

Participant's Contact Details (if appropriate):

jack@prisma.co.nz

Date: 11 DEC 2017

Approved by the Auckland University of Technology Ethics Committee on 20/11/2017 AUTEC Reference number 17/384.

Note: The Participant should retain a copy of this form.

Consent Form

Project title: ***Investigating the effectiveness of BIM-BMS Integration on Managing Existing Educational Building Facilities in New Zealand***

Project Supervisor: ***Dr Ali GhaffarianHoseini, Dr Nicola Naismith, and Prof John Tookey***

Researcher: ***Tongrui ZHANG***

- O I have read and understood the information provided about this research project in the Information Sheet dated 29/10/2017. MAJORITY.
- ✓ I have had an opportunity to ask questions and to have them answered.
- ✓ I understand that my name, position and affiliation will be disclosed in the publications and thesis for academic purpose.
- ✓ I understand that notes will be taken during the focus group and that it will also be audio-taped and transcribed.
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- ✓ I agree to take part in this research.
- O I wish to receive a summary of the research findings (please tick one): Yes ✓ No O

Participant's signature: ....

Participant's name: CRAIG SKELTON

Participant's Contact Details (if appropriate):

AUT

027 683 7897

....

....

Date: 06/12/17.

Approved by the Auckland University of Technology Ethics Committee on 20/11/2017 AUTEC Reference number 17/384.

Note: The Participant should retain a copy of this form.

Appendix C: Experimental Records

Time 8/07/18	#1 (°C)	#2 (°C)	#3 (°C)	#4 (°C)	#5 (°C)	#6 (°C)	#7 (°C)	#8 (°C)	#9 (°C)
00:00:00	34.3	22.4	22.5	22.1	20.7	21.4	21.8	22.4	21.8
01:00:00	34.1	22.1	22.4	22.0	20.6	21.2	21.5	21.9	21.7
02:00:00	23.3	21.9	21.7	21.7	20.6	21.5	21.8	22.5	21.5
03:00:00	31.2	22.0	21.9	21.9	20.7	21.3	21.7	21.9	21.5
04:00:00	33.2	22.2	22.3	22.1	20.8	22.0	22.1	22.8	21.5
05:00:00	34.1	22.1	22.4	22.0	20.8	21.2	21.5	21.9	21.5
06:00:00	24.2	21.9	21.8	21.8	20.8	21.5	21.8	22.6	21.5
07:00:00	22.8	21.9	21.4	21.7	20.5	21.7	22.0	22.4	21.5
08:00:00	22.2	21.7	21.0	21.5	20.6	21.4	21.8	22.4	21.4
09:00:00	22.2	21.6	20.9	21.5	20.8	21.3	21.8	22.1	21.3
10:00:00	22.4	21.8	21.1	21.8	21.2	21.7	22.1	22.6	21.4
11:00:00	22.3	21.7	21.1	21.8	21.1	21.7	22.1	22.8	21.4
12:00:00	33.1	21.8	21.5	21.9	21.2	21.4	21.8	22.0	21.4
13:00:00	33.4	22.1	22.2	22.1	21.1	21.4	21.8	21.9	21.5
14:00:00	23.2	21.8	21.7	21.9	21.0	21.8	22.2	22.7	21.5
15:00:00	22.9	21.9	21.6	22.1	21.2	21.9	22.4	23.0	22.1
16:00:00	22.6	21.9	21.5	22.0	21.2	21.8	22.4	22.7	21.8

17:00:00	22.2	21.8	21.4	21.8	20.9	21.7	22.2	22.2	21.6
18:00:00	22.1	21.6	21.2	21.6	20.7	21.5	22.1	21.8	21.5
19:00:00	22	21.6	21.1	21.4	20.5	21.9	22.2	22.7	21.4
20:00:00	22.2	21.7	21.1	21.4	20.5	21.9	22.2	22.7	21.4
21:00:00	36.9	21.4	22.2	21.6	20.8	21.3	21.8	22.4	21.9
22:00:00	38.4	22.2	22.5	22.1	21.1	21.5	21.9	22.5	21.9
23:00:00	34.8	22.4	22.5	22.1	21.1	21.5	21.9	22.5	21.9