Digitising key workflows in the precast concrete supply chain : a BIM cloud-enabled system for productivity improvement

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2020

Phang, T. C. H. (2020). Digitising key workflows in the precast concrete supply chain : a bim cloud-enabled system for productivity improvement. Doctoral thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/146704>

<https://doi.org/10.32657/10356/146704>

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**DIGITISING KEY WORKFLOWS IN THE PRECAST
CONCRETE SUPPLY CHAIN: A BIM CLOUD-ENABLED
SYSTEM FOR PRODUCTIVITY IMPROVEMENT**

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SCHOOL OF CIVIL & ENVIRONMENTAL ENGINEERING

2020

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CONCRETE SUPPLY CHAIN: A BIM CLOUD-ENABLED
SYSTEM FOR PRODUCTIVITY IMPROVEMENT**

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A thesis submitted to the Nanyang Technological University in partial
fulfilment of the requirement for the degree of
Doctor of Philosophy

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarised materials, and has not been submitted for a higher degree to any other University or Institution.

30 November 2020

Date

Thomas Phang Chin Hin

Supervisor Declaration Statement

I have reviewed the content and presentation style of this thesis and declare it is free of plagiarism and of sufficient grammatical clarity to be examined. To the best of my knowledge, the research and writing are those of the candidate except as acknowledged in the Author Attribution Statement. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

30 November 2020

Date

Assoc Prof. Robert L. K. Tiong

Authorship Attribution Statement

This thesis contains material from two papers that were submitted in the following peer-reviewed journal (s) where I was the first and/or corresponding author.

Part of this research is published as Thomas C. H. Phang; Chen Chen; Robert L. K. Tiong, A new model for identifying critical success factors influencing BIM adoption from precast concrete manufacturers' view. *ASCE's Journal of Construction Engineering and Management*. DOI: 10.1061/(ASCE)CO.1943-7862.0001773.

The contributions of the co-authors are as follows:

- I prepared the manuscript drafts. The manuscript was revised by Dr. Chen Chen and Associate Professor Robert Tiong.
- I co-designed the study with A/Prof Robert Tiong and conducted the survey myself. I have also analysed the initial raw data.
- I have compiled the questionnaire by getting relevant inputs from selected PC companies across the region.
- Dr Chen Chen suggested employing Learn to rank (LTR) approaches which gives a better factor stratification and has no requirement on sample size.

Portion of chapter two, four and six has been submitted as Thomas C. H. Phang; Chen Chen; Robert L. K. Tiong, Application of BIM and cloud technology to automate the submittal process for precast plant production. *Journal of Construction Management and Economics*.

The contributions of the co-authors are as follows:

- I prepared the manuscript drafts. The manuscript was reviewed by Associate Professor Robert Tiong and Dr. Chen Chen.
- I have conducted and compiled all the relevant data for the case studies through extensive interviews with the respective actors.
- I have also analysed the initial raw data together with the selected PC company.

30 November 2020

Date

A handwritten signature in black ink, appearing to read 'Phang Chin Hin', written in a cursive style.

Thomas Phang Chin Hin

ACKNOWLEDGEMENT

To God be the glory.... “If any of you lacks wisdom, you should ask God, who gives generously to all without finding fault, and it will be given to you.” James 1:5.

The author would like to express my sincere gratitude and appreciate for my supervisor, Associate Professor Robert Tiong, for his guidance and support of my PhD study and research. I would also like to thank the thesis advisory committee: Assistant Professor Holden Li and Assistant Professor Zhu Feng for their insightful comments and questions.

For her unwavering support and encouragement, the author would like to thank his wife, Lydia. She has been the pillar of strength, always by the author side in many difficult moments.

The author would like to thank the precast concrete manufacturer who provided all the necessary data and permissions for site visits. Because of their willingness to provide valuable information, the outcomes of this research could possibly assist the PC industry to become technology forerunner.

Finally, the author wishes to thank his company Trimble SEA and the various people for their contribution to this research; Mr. Alfred Hng and Mr Chester Tan, for their valuable technical support to develop the PLMS system.

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ABSTRACT

A typical construction project will entail many players at various stages and involves functions such as design, construction, and fabrication. It largely includes the client, designer, main contractor, and a precast concrete (PC) manufacturer's involvement from the start to finish of the project. Earlier research has revealed that traditional construction practices caused many problems associated with fragmentation, predominantly due to the lack of communication and coordination between stakeholders. This has led to unnecessary delays and disputes among stakeholders during the construction stage. The problem is further worsened as the work flows downstream to sub-contractors such as PC manufacturers.

Across the globe, the governments of developed countries have been implementing building information modelling (BIM) in the construction industry to transform the value chain to enhance the workflows in the construction industry. However, the literature on BIM focusing on the precast concrete segment is under-developed. And as off-site fabrication of building components is becoming progressively common, it becomes imperative to focus on PC manufacturers and identify areas of enhancement. This in turn will increase the overall productivity of the PC supply chain.

This research takes the perspective of PC manufacturers. The study first establishes a baseline understanding of the status of BIM adoption among the PC manufacturers. As such, a BIM adoption model is created from the perspectives of PC manufacturers to explain the organisations' BIM adoption status, and the PCBIM hexagon framework was proposed to identify the critical success factors (CSFs) that affect their BIM adoption status. A total of eight factors have been identified as the CSFs to BIM adoption. In addition, these CSFs were further assessed to determine factors that directly contribute to productivity improvement and the PC-CSF performance analytical model is developed. A total of four CSFs have been shortlisted: (1) BIM utilisation, (2) top management commitment, (3) team coordination and (4) information sharing. The author called these factors the "PC-CSF performance factors".

The results concluded that the CSFs for BIM adoption can certainly facilitate PC manufacturers towards higher levels of technology utilisation, however not all the CSFs directly contribute to the productivity improvement of the PC manufacturers. To demonstrate and validate the usefulness of the PC-CSF performance analytical model for real-world problem-solving, an established PC manufacturer was selected to conduct the case studies. Three key workflows in the PC supply chain were identified and the four PC-CSF performance factors were applied collectively. The field results have proven that the combined benefits of the PC-CSF performance factors can improve the productivity of the PC manufacturer and its supply chain.

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LIST OF PUBLICATIONS

Phang, T. C., Chen, C., and Tiong, R. L. (2019), "A new model for identifying critical success factors influencing BIM adoption from precast concrete manufacturers' view", ASCE Journal of Construction Engineering and Management, Vol. 146, No.4.
[https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0001773](https://doi.org/10.1061/(ASCE)CO.1943-7862.0001773)

Phang, T. C., Chen C., and Tiong, R. L. (under review), "Application of BIM and cloud technology to automate the submittal process for precast plant production", Journal of Construction Management and Economics.

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LIST OF ABBREVIATIONS

3D	Three-dimensional
AEC	Architecture, engineering, and construction
API	Application programming interface
BIM	Building Information Modelling
CSF(s)	Critical success factor(s)
DCG	Discounted cumulative gain
DfMA	Design for Manufacturing and Assembly
D/O	Delivery order
ICPH	Integrated construction and prefabrication hub
IDD	Integrated digital delivery
IDT	Innovation Diffusion Theory
IFC	Industry Foundation Class
IoT	Internet of things
IT	Information technology
JIT	Just-in-time
LTR	Learn to rank
LOD	Level of development
MC	Main contractor
MEP	Mechanical, electrical, and plumbing
MDL	Master drawing list
PC(s)	Precast Concrete(s)
PCBIM	Precast Concrete Building Information Modelling
PC-CSF	Precast Concrete - Critical Success Factor
PLMS	Production Logistic Management System
PPVC	Prefabricated prefinished volumetric construction
RFID	Radio frequency identification
SITD	System for Inventory Tracking and Delivery
SPCP	System for Progress Claim and Payment
SME(s)	Small and medium-sized enterprise(s)

SSDA	System for Shop Drawing Approval
TAM	Technology Acceptance Model
UID	Unique identity
UTAUT	Unified Theory of Acceptance and Use of Technology
VSM/A	Value stream mapping and analysis

LIST OF NOMENCLATURES AND SYMBOLS

α	Cronbach's alpha
i	Index of survey factors, $i = 1, \dots, n$
j	Index of survey respondents, $j = 1, \dots, m$
l^j	Judgment scores to the factors given by respondent j
r^j	Ranking of the factors in light of l^j
π	Best ranking
θ	Chromosome. Its genes represent the judgment scores to the factors
ϑ	Ranking of the factors in light of θ
v^j	Variance between r^j and ϑ
φ	Population size
μ	Number of best individuals for parent selection
λ	Number of generated children
ξ	Number of iterations required
P_c	Crossover probability
P_m	Mutation probability
γ	Number of independent GA runs
y	Dependent variable in the multiple regression model
x_k	Predictor variable in the multiple regression model, $k = 1, \dots, n$
ϵ	Residual error in the multiple regression model
β_k	Regression coefficient, $k = 1, \dots, n$
$\bar{x}_H$	Harmonic mean

Flow of work

Predefined-task

Predefined-task with processing time indicated

Start and end of a task

Total wait (queue) time of the predefined-process with duration indicated

Task eliminated

Task optimised

A task or an action taken

Chapter 1 : Introduction

This chapter provides the research background such as the role and importance of precast concrete in the construction industry as well as the motivations of this study. The research gaps associated with the PC manufacturer and its supply chain are presented, followed by the research aim and objectives to address those research gaps. Finally, each chapter is briefly introduced, and the summary of the research achievements is given.

1.1 Background

The adoption of Building Information Modelling (BIM) is considered as a major technological shift in the construction industry in Singapore. As projects become more complex, BIM enables companies to conduct business, communicate and collaborate among stakeholders much more effectively and thus, maximising their profitability. There are numerous studies regarding the benefits as well as challenges of BIM implementation (Bryde et al., 2012; Migilinskas et al., 2013). However, the implementation of BIM among precast concrete (PC) manufacturers in Singapore has not been thoroughly explored.

In Singapore, the Building and Construction Authority (BCA) has implemented a BIM roadmap to help the construction sector build BIM capability and capacity. As such, the BIM Steering Committee was set up to steer the implementation of the BIM Roadmap (BCA, BCA's Building Information Modelling Roadmap, 2019), and led the development of the "Singapore BIM Guide" (BCA, Singapore BIM Guide version 2, 2013). BCA has also made available a series of initiatives to encourage BIM adoption in the construction industry (BCA, The Second Construction Productivity Roadmap, 2015). For example, this includes the BCA BIM Fund which helped companies to establish BIM capability by covering the costs for the purchase of hardware and BIM software, training and consultancy services (BCA, Technology Adoption: Building Information Model (BIM) Fund V2, 2015). In addition, the government has also made it compulsory for the industry to submit architectural, structural and mechanical and electrical plans for approval in the BIM format (BCA, Deadlines for Projects Requiring Mandatory BIM e-Submission for Regulatory Approval, 2015).

BCA has been promoting the use of buildable design to increase site productivity. As an effort to encourage the wider use of precast concrete, a guidebook (BCA, CONQUAS 21 Enhancement Series, 2019) has been published to help PC manufacturers, especially in residential housing. In October 2017, BCA once again announced the Construction Industry Transformation Map (ITM) to promote green building design, design for manufacturing and assembly (DfMA) and integrated digital delivery (IDD). To realise these visions, BCA will increase DfMA and IDD adoption by building up experience, capacity and capability of the industry. The Prefabricated Prefinished Volumetric Construction (PPVC) guidebook was launched, providing a practical guide to construction companies to design, fabricate

and install PPVC components (BCA, Design for Manufacturing and Assembly (DfMA), 2019). Thus, PC manufacturers will continue to play a pivotal role in the Singapore construction eco-system.

In recent years, the use of precast concrete has gained momentum in Singapore, and many PC manufacturers in Singapore have already adopted BIM. However, efforts should also be focussed on the PC supply chain to attain sustainable improvement and productivity. The basic idea is to do all activities as lean as possible (Kosonen & Buhanist, 1995), eliminating any activity that does not add value to the PC product. Essentially, the combination of both information technology (IT) and an efficient process can certainly improve the PC manufacturer and its supply chain productivity and profitability.

1.2 Research gaps

BIM is currently a new way of approaching the design, construction and maintenance of buildings in Singapore. To gain productivity, off-site fabrication of building components is becoming progressively common and the use of BIM models to support PC manufacturers is a natural progression.

1. Although many studies have reported on the benefits and challenges of BIM versus traditional construction, there is hardly any mention of the critical success factors that will successfully transform PC manufacturers through BIM adoption. This is partly due to the challenges or lack of a common model to explain the BIM adoption status.
2. Many studies have been conducted to improve PC supply chain productivity and efficiency in information tracking, monitoring and sharing. And various technologies such as BIM and radio frequency identification (RFID) have been deployed to facilitate the implementation of off-site construction. However, none has given an in-depth consideration and provision of real-world solutions for improving the productivity of workflows in the pre- and post-production phases of a typical PC supply chain.
 - The studies on factors of delay were mostly focussed on data collection and did not thoroughly solve the pertinent problems. Besides, no research was done that focussed on improving key pre-production process such as shop drawing approval for production.

- The studies on the automatic identifying, tracking and locating of PC panels at storage yards or in delivery are still lagging. As most studies only investigated the management and tracking of inventory as a singular process, their foci were mainly on data gathering and did not thoroughly solve the information communication problems encountered by the key parties across the PC supply chain.
 - The current studies on claim and payment were mostly focussed on standalone solutions, targeted at general constructors' usage. There is currently no study that aimed at combining the capabilities of BIM and cloud technology to provide a centralised database for PC manufacturers to manage their progress claim and payment workflow.
3. Lastly, the current studies on lean management predominantly focus on improving the efficient of the production operations during the precast production phase. To bring about a productivity improvement to the entire PC supply chain, key workflows in the pre- and post-production phases need to be examined and addressed. In other words, the utilisation of the transformative capabilities of IT combined with lean practice to improve key workflow across the entire PC supply chain is under-developed.

1.3 Research aim and objectives

In view of the above discussion, this study aims to establish a baseline understanding of the present BIM adoption status among PC manufacturers, and to offer real-world solutions to propel the precast industry towards higher levels of technology utilisation and productivity. The board research gaps presented in the previous section composed of three interrelated questions:

- 1 Is there a BIM adoption model to explain the PC manufacturers' BIM adoption status?
- 2 What are the critical success factors (CSFs) that PC manufacturers should consider for successful BIM adoption?
- 3 How may these CSFs enable the PC manufacturer and its supply chain to attain a higher level of productivity?

To answer these questions, five research objectives have been identified:

1. To establish a BIM adoption model from the perspectives of PC manufacturers to explain organisations' BIM adoption status.
2. To develop the PCBIM hexagon framework for the determination of the CSFs affecting BIM adoption.
3. To assess and identify the CSFs that directly contribute to productivity improvement to the PC manufacturers.
4. To demonstrate and validate these factors are useful for the PC manufacturer and its supply chain.
5. To analyse and present the productivity improvement data across the identified key workflows in the PC supply chain.

1.4 Outline of Thesis

This thesis is organised into seven chapters in the following sequence.

Chapter 1: serves as an introduction to the research. It discusses the significance, aim and objectives of the research. The outline of the thesis and research achievements are presented.

Chapter 2: provides a systematic literature review of the research. Firstly, it examines the body of studies on BIM adoption in the AEC industry. It then proceeds to explore various adoption models, the key drivers for BIM adoption, the proposed CSFs and ranking methods used in past research. Secondly, it examines the existing studies on the PC supply chain as well as the lean management for PC supply chain productivity optimisation. This chapter also investigates IT tools (such as BIM cloud and visualisation technology) and how they may be utilised to improve productivity across the key workflows in the PC supply chain.

Chapter 3: presents the research methodology of the research. The first part of the study was to identify CSFs that influence their success in the BIM adoption and then shortlist those CSFs that contribute directly to productivity improvement. A model called “PC-CSF performance analytical model” was then created to assist PC manufacturers navigate towards a higher level of productivity improvement. In order to test and demonstrate the benefits and implications of the PC-CSF performance analytical model, key workflows in

the PC supply chain were identified as case studies, namely (1) approval of shop drawings for production, (2) tracking and delivery of inventory and (3) progress claim and payment.

Chapter 4: presents the results and the analysis of the questionnaire survey that was conducted. The CSFs of BIM adoption as well as those factors directly contributing to productivity improvement of the PC manufacturers are discussed. Taking the perspective of the PC manufacturer, the present key workflows of the PC supply chain are identified, the current tasks and issues are discussed.

Chapter 5: describes the development of the Production Logistic Management System (PLMS). It comprises three modules that addressed and improved the identified workflows as listed in chapter 4. The PLMS supports the application of the PC-CSF performance factors and is pivotal to the enhancement of the newly developed workflows.

Chapter 6: presents the usefulness of the PC-CSF performance factors in real-world scenarios by means of case studies. Utilising the value stream mapping and analysis technique, the productivity improvements it brings to the newly developed workflows are measured and discussed.

Chapter 7: provides the conclusions, contributions to academic and industry, discussions and recommendations of the research. The scope for future research is also discussed.

1.5 Summary of research achievements and contributions

This research can contribute to the existing literature in the following ways. By means of empirical studies, the CSFs that influence their success in the BIM adoption were identified for the first time. And factors that contribute directly to productivity improvement were also shortlisted.

The following have been achieved:

1. A conceptual model of BIM adoption for PC manufacturers is established to explain organisations' BIM adoption status and furthermore, serve as a guide for the PC manufacturers to upgrade themselves to higher levels of technology utilisation, provided that the CSFs are accessible.

2. A PCBIM hexagon framework to identify the CSFs affecting BIM adoption from PC manufacturers' view. A total of eight CSFs were identified
3. A regression model called "PC-CSF performance analytical model" to assist PC manufacturers navigate towards a higher level of productivity. A total of four factors were identified as influential to the improvement of productivity.

To demonstrate and validate the usefulness of the PC-CSF performance analytical model in real-world scenarios. The four PC-CSF performance factors were applied collectively to improve the productivity of the key workflows in the PC supply chain. As such,

4. The application of the PC-CSF performance factors brought about productivity improvement to the key workflows in the PC supply chain, namely (1) approval of shop drawings for production, (2) tracking and delivery of inventory and (3) progress claim and payment.
5. A bespoke BIM cloud-enabled solution called the Production Logistic Management System (PLMS) was developed to support the application of PC-CSF performance factors. The system comprises three modules to address real-world challenges in the supply chain, namely (1) System for Shop Drawing Approval (SSDA), (2) System for Inventory Tracking and Delivery (SITD) with Proof of Delivery (POD), (3) System for Progress Claim and Payment (SPCP) and a customisable status dashboard to allow real-time observations of project progress status.

Chapter 2 : Literature review

This chapter provides a comprehensive review of existing studies relating to: (1) BIM adoption in AEC industries, the various adoption models, the key drivers and critical success factors for BIM adoption as well as the ranking methods used. (2) The PC supply chain, the current IT usage among stakeholders and various studies that address pertinent issues in the PC pre- and post-production phases. The present lean practice and application to the PC industry are also examined. Lastly, (3) relevant information technology that can transform and enhance the productivity of the PC supply chain workflows.

2.1 The adoption of BIM

The adoption of BIM is considered a major technological shift for the construction industry. BIM provides a collaboration platform that contributes to synchronise the work among different stakeholders in the PC supply chain. To seek previous research on BIM adoption in PC manufacturing, a search for PC literature was performed in Scopus. The Scopus database was selected because it has a search engine covering more journals, with better indexing process and more recent publications within the civil engineering, construction project management (PM) and construction IT, compared to any other available digital sources such as Web of Science (Oraee et al., 2017).

In the domain of precast, a wide range of interchangeable terms have been used, such as “prefabricated construction” or “modular construction”. By reviewing earlier studies (Ahuja et al., 2018; Arayici et al., 2012; Azhar, 2011; Migilinskas et al., 2013; Wang et al., 2018), keywords used for the search were selected based on the earlier papers. A list of terms for precast that were used interchangeably were noted as keywords. To ensure a comprehensive search, the author has also considered the differences in American and British spelling, for instance, the word “modeling” versus “modelling”. Figure 2-1 shows the search criteria set. Also, the word “implementation” and “adoption” have been used interchangeably in different papers (Ahuja et al., 2018; Tulenheimo, 2015).

Figure 2-1 Search criteria

Since the author was focusing on research publications, only journals were considered, and only papers published in English were selected for this study. A total of 145 publications matched the search criteria listed above. Further refinements of the results were achieved by screening out articles that did not fall under the scope of precast in civil engineering, building management and construction. As a result, the final count of papers was at 64. Appendix A provides the details of the selected papers after the screening process.

An analysis of keywords revealed the frequently studied research themes include (1) design and standards (e.g., Design for Manufacturing and Assembly - DfMA), (2) construction project management, (3) BIM and information technology, (4) BIM adoption and implementation as well as (5) education and training. The grouping was determined through consensus discussion among the researchers involved at the time of this research. A total of 18 studies were found that addressed the benefits as well as challenges of BIM adoption and implementation. To gain an in-depth understanding of the main research topics in this domain, VOSviewer software was used. It is a visualisation tool to construct occurrence networks of important terms extracted from the 18 papers. Each circle represents an item, and the higher the frequency of occurrence, the larger the labels and size of the circles. Referring to Figure 2-2, it suggests that previous BIM adoption studies focussed predominantly on the architectural design and construction industry in general, and few were from the perspective of PC manufacturers.

For instance, Abanda et al., (2017) studied the implications of BIM systems on off-site manufacture, highlighting the benefits and challenges of BIM versus traditional construction. Arunkumar et al. (2018) discussed the attitude of the professionals in AEC industry regarding the positive and negative factors influencing the implementation of BIM in the AEC industry. Chan et al. (2019) delved into the perceived benefits of and barriers to BIM implementation in the Hong Kong construction industry. Enshassi et al. (2019) studied the factors that limit BIM implementation in the construction industry. And Son et al. (2015) evaluated the factors that can potentially facilitate architects' adoption of BIM through an extension of the technology acceptance model.

Figure 2-2 Occurrence network visualisation of terms

In other words, there was no explicit body of knowledge focussed on investigating the critical success factors that influence the adoption of BIM among the PC manufacturers. The availability of such information can certainly assist PC manufacturers who are thinking of choosing or have already chosen BIM technology to apply successfully in their companies.

2.1.1 Review of the adoption models

To identify the factors involved in the acceptance and adoption of innovation, researchers have proposed many theories. The most basic ones are the Technology Acceptance Model (TAM), the Innovation Diffusion Theory (IDT), and the Unified Theory of Acceptance and Use of Technology (UTAUT). The TAM was developed by Davis (1989) to model how users come to accept and use new technology. It is comprised two specific factors that influence users' behaviour of how and when they will use a new technology, they are: (1) perceived usefulness and (2) perceived ease-of-use. On the other hand, the IDT was proposed by Rogers (1962) to describe the process through which an innovation is

communicated over a period of time in a social system and is associated with uncertainties. It includes five main factors: (1) relative advantage, (2) compatibility, (3) complexity, (4) trialability, and (5) observability. Many adoption models integrate elements of the TAM and the IDT. For example, the Prevention through Design Adoption Readiness Model (PtD ARM) proposed by Weidman et al. (2016) for improvement of worker readiness to adopt ventilated tools. In this regard, the UTAUT was proposed by Venkatesh, et al. (2003) to combine the IDT and the TAM. It has four key variables: (1) performance expectancy, (2) effort expectancy, (3) social influence, and (4) facilitating conditions. The first three will decide the usage intention and behaviour while the fourth will decide the users' behaviour.

Research studies have confirmed that BIM adoption in construction is analogous to the innovation adoption process (Hosseini et al., 2015). Hence, the models above-mentioned are popularly used to identify the factors influencing BIM adoption. For example, Hosseini et al. (2016) provided an insight into the current state of BIM and the main barriers to BIM adoption within Australian small and medium-sized enterprises (SMEs) grounded on the IDT. Gledson and Greenwood (2017) made use of the IDT to examine the process through which the innovation of 4D BIM has been communicated to and adopted over time by the construction planners in the United Kingdom. In addition, Gokuc and Arditi (2017) investigated the impact of BIM on the performance of design firms as perceived by designers by applying the TAM. Nevertheless, researchers pointed out that in addition to the advantages of the technology, the characteristics of the user, social attitude, trust, and other causal factors also affect BIM adoption (Ahuja et al., 2018). Therefore, Ahjua et al. (2018) investigated the adoption of BIM in emerging markets based on the technology-organisation-environment framework (similar to the UTAUT) which broadly categorises the affecting factors along these three dimensions. Additionally, Hong et al. (2018) modelled an organisation's decision-making process when it comes to adopting BIM by conducting a quantitative analysis stemming from the UTAUT to identify factors that strongly affect SMEs' BIM adoption decision.

Since the construction industry constitutes numerous organisations with different kinds of managerial and financial constraints, it is unlikely that a singular approach exists for these organisations to adopt BIM at the same pace (Ayinla & Adamu, 2017). A phenomenon known as the "digital divide" arises reflecting the lag experienced by some firms in exploiting new innovations and opportunities. On the one hand, the key actors in the BIM

adoption and diffusion chain can be divided into four main groups congruent to Maslow's hierarchy of needs: (1) Group 0 - late majority and laggards, (2) Group 1 - early majority, (3) Group 2 - early adopters, and (4) Group 3 - innovators (Singh & Holmstrom, 2015). Typically, innovators are risk takers while the rest become more and more conservative and sceptical towards innovation. On the other hand, the statuses of BIM maturity in an organisation can be divided into four main levels too: (1) Level 0 – the use of unmanaged CAD, (2) Level 1 – a mix of 2D and 3D information, (3) Level 2 – collaborative BIM, and (4) Level 3 – integrated BIM (Bew & Richards, 2008). Therefore, BIM adoption models need to address the specific needs and business values of different kinds of organisations in different regions. Appendix C provides additional information on the BIM maturity statuses and BIM adopter's model.

Singh and Holmstrom (2015) firstly linked Roger's theory on technology adoption and innovation diffusion with Maslow's theory on human needs to study BIM adoption in the AEC industries. Then, Ayinla and Adamu (2017) proposed an integrated BIM adoption model that mixes the Singh and Holmstrom innovation adopter's model with the Bew-Richards BIM maturity model to classify the AEC organisations and investigate how the digital divide gap phenomenon relates to BIM adoption. They found that the size of an organisation does not necessarily make it an innovator. This is an interesting finding as it contradicts the Schumpeterian Hypothesis which states that the level of innovation within firms is positively associated with firm size. Another interesting work is provided by Herr and Fischer (2018). They developed an extended BIM adoption model accommodating the Bew-Richards model along one axis, building lifecycle stages along the second axis, and a dimension for quantification along the third axis, to investigate temporal and collaborative dimensions of BIM adoption across the AEC industries.

2.1.2 Critical success factors for BIM adoption

With so many tasks occurring simultaneously during the BIM adoption process, it is not realistic to consider all of the key factors, especially when resources are constrained. The concept of CSFs was first proposed in the late 1970s by John Rockart (1979). CSFs are important to new technology adoption because they allow companies to focus their efforts on building their capabilities to meet those CSFs. Suggestions for the factors affecting BIM adoption are abundant. However, most of the earlier works introduced sparse

recommendations based on successful case studies (Kuprenas & Mock, 2009; Manning & Messner, 2008). Because case studies are insufficient to provide a complete list of solutions, the later researchers tend to compile the scattered solutions and quantitatively analyse the criticality and priority through survey methods.

Table 2-1 summarised the proposed CSFs in the published literature. It is found the CSFs in different studies vary due to the difference in survey respondents and regions, which are consistent with the previous discussion on BIM adoption models. Thus, a conclusion was made that the research methods play a deterministic role in deciding the CSFs.

Table 2-1 CSFs for enhancing BIM adoption identified in literature review

Papers	CSFs	Respondents
Won et al. (2013)	<ol style="list-style-type: none"> (1) Willingness to share information among project participants (2) Maser BIM model team/manager (3) Effective collaboration among project participants (4) Organisational structure to support BIM (5) Continuous investment (6) Leadership of senior management (7) Information-sharing protocols (8) BIM training programs (9) Technical supports for interoperability issues (10) Standardised work procedures for BIM 	World-leading BIM experts
Son et al. (2015)	<ol style="list-style-type: none"> (1) Top management support (2) Subjective norm (3) Compatibility (4) Computer self-efficacy 	Architects at Korean design organisations that actively use BIM
Tsai et al. (2014; 2014b)	<ol style="list-style-type: none"> (1) Support from top management (2) Functionality (3) Design validation of BIM tools (4) The definition of project goals before forming teams (5) Coordination and integration among the professions 	Taiwan AEC industry's business owners, managers, architects, engineers, designers, contractors, subcontractors and BIM model builders who had experience with CAD and are in the process of changing to BIM technology
Liao and Teo (2017)	<ol style="list-style-type: none"> (1) Producing models and drawings for construction and fabrication (2) Integrating model management tools with enterprise systems to share data (3) High accuracy of model-based documentation (4) Data sharing and access on BIM platforms (5) BIM vision and leadership from the management (6) Changes in organisational structure and culture (7) Training on new skillsets and new ways of working (8) Stakeholders seeing the value of adopting their own part of BIM 	BIM experts in Singapore

	(9) Owner's requirement and leadership to BIM adoption (10) 3D visualisation enabling design communication (11) Regulatory agencies' early participation to BIM use (12) Design coordination between disciplines through clash detection and resolution (13) Gaining competitive advantages from full BIM use	
Amuda-Yusuf (2018)	(1) Standard platforms for integration and communication (2) Cost of development (3) Education and training (4) Standardisation (product and process) (5) Clear definition and understanding of users' requirement	Nigerian AEC industry's architects, engineers, quantity surveyors engaged in contracting firms, consulting firms, public and private clients' organisations
Olawumi and Chan (2019)	(1) Increased number of subcontractors experienced with BIM projects (2) Greater awareness and experience level within the firm (3) Increased involvement of project stakeholders in green projects	Experts from the academics and industrial practitioners

2.1.3 Key drivers for PC BIM adoption

The factors impeding innovation are complex. There is a large body of literature dedicated to surveying key drivers for BIM adoption. Tsai et al. (2014) summarised the previous findings into the following six areas: (1) the organisation, (2) the application, (3) the tool, (4) the project team, (5) the process, and (6) the business model. However, these areas are all at the organisation level and the importance of the environment has not been thoroughly addressed. For example, competent and supportive clients/owners can facilitate BIM adoption (Cao et al., 2014). So, Poirier et al. (2015) later offered a three-level perspective. They found innovation drivers are active at (1) the organisational level (intra-firm), (2) the project network level (inter-firm), and (3) the industry level (trans-firm).

The construction industry is dominated by SMEs. For example, they account for 97% of businesses across the construction sector in the European Community (Dick & Payne, 2005) and 98% in Australia (Hosseini, et al., 2016). SMEs usually lack in-house technology capabilities, overall rates of innovation in the industry are lagging behind, especially when compared with more innovative sectors like manufacturing (Reichstein et al., 2005).

A construction project involves various project participants and stakeholders. In many cases, an organisation would like other partner organisations to use BIM for project communication purposes (Hong et al., 2018). Architects, engineers, general contractors are usually the most influential drivers. Survey results reveal that client demand has significantly driven BIM uptake (Eadie et al., 2015). As a result, pressures from the market cannot be neglected. Therefore, the following areas need to be closely examined: (1) the government, (2) the eco-system, (3) the company, (4) the team, (5) the process, and (6) the tool.

The government: According to Porter’s Diamond model (Porter, 1990), governments can play a pivotal role in encouraging the development of the construction industry in the country. Governments provide the BIM adoption strategies; establish the necessary guidelines, policies and mandates as well as investing in capabilities and capacities of the workforce. They can motivate companies to use technologies to improve productivity by granting subsidies or other financial incentives.

In various countries, governments make efforts in creating an effective environment for construction innovation (Lim, 2014). Government policy guidelines have promoted BIM adoption. Table 2-2 lists these government activities in major nations around the world.

Table 2-2 BIM policies around the world

Region	Country/ Organisation	Year started	BIM initiatives and mandate
Asia	China/ Ministry of Housing and Urban- Rural Development (MOHURD)	2011	BIM has been included as part of the National 12th Five Year Plan (from 2011 to 2015) and has formulated a BIM framework. MOHURD has since delivered its thirteenth Five-Year Plan (which runs 2016 to 2020) and the Chinese BIM policy now includes provisions for the adoption of BIM to be driven by government.
	Hong Kong/ The Hong Kong Institute of Building Information Modelling (HKIBIM)	2009	HKIBIM was established in 2009 and the Hong Kong Housing Authority set a target of full BIM implementation by 2015.
	Japan/ Ministry of Land, Infrastructure and Transport (MLIT)	2010	In 2010, Japan announced the start of BIM pilot project in government building and repairs. Japan Institute of Architects (JIA) released the BIM guidelines in 2012.
	Malaysia/ The Construction Industry Development Board (CIDB)	2011	CIDB has been given the mandate to lead BIM uptake in Malaysia. Since then, it has initiated several activities to improve BIM implementation such as setting up BIM projects for national reference, created committees to monitor BIM

			activities, and conducted BIM seminars and workshops.
	Singapore/ Building and Construction Authority (BCA)	2011	Introduced national-wide implementation roadmap in 2011. In 2012, BIM became part of public sector building project procurement. BIM was introduced for architectural submission in 2013, structural and M&E submissions in 2014. From 2015 onwards, BCA requires mandatory use of BIM.
	South Korea/ Ministry of Land, Transport and Maritime Affairs (MLTM)	2010	Since 2010, the Korean government has been gradually increasing the scope of BIM-mandated projects. In 2012, a detailed report on the status of BIM adoption and implementation was published.
Europe	Denmark/ Bygningssstyrelsen (The Danish building and Property Agency)	2007	Its use became mandatory in federal projects during 2007. Danish state establishments such as the Palaces & Properties Agency, the Danish University Property Agency, and the Defence Construction Service require BIM to be used for their projects.
	Finland/ Senate Properties (The Finnish state property services agency)	2007	Finland mandated that any design software needed to pass Industry Foundation Class (IFC) Certification. Mandatory for infrastructures project since 2014.
	France/ Centre Scientifique et Technique du Batiment (CSTB)	2014	In 2017, as part of the French strategy for digitising the construction industry, BIM was mandated for France. An official French standardisation roadmap was made public.
	Germany/ Platform Digitales Bauen (Digital Building Platform).	2015	BIM task group called Digital Building Platform was to develop a national BIM strategy. BIM will be mandatory for all transportation projects in Germany by the end of 2020.
	Netherlands/ Rijksgebouwendienst (RGD)	2011	RGD is the government buildings agency within the Ministry of the Interior and Kingdom Relations that manages government buildings. They have introduced the RGD BIM Norm (BIM standard) which was updated in 2012.
	Norway/ Statsbygg (Norwegian Directorate of Public Construction and Property)	2007	Since 2007, several large public clients use of BIM in open formats (IFC) in most or all of their projects. And have required IFC/BIM for new buildings since 2010.
	Sweden/ BIM Alliance Sweden	2014	BIM Alliance created in 2014 to increase the uptake of BIM. This resulted in the development of BIM and information management guidelines with governmental property developers.
	The United Kingdom/ Department for Business, Innovation & Skills (BIS)	2011	In 2011, the UK government published its BIM strategy. The government requires mandatory use of BIM in the public sector (£5 million) from 2016 onwards. Their target is to become a BIM leader in the European region.
North America	Canada/ Canada BIM Council	2008	Canada BIM Council drove adoption of standardised models in architecture, engineering, and construction. It also manages national-wide implementation and introduces good practices and standards, requiring the use of BIM in public construction projects.
	The United States/ General Services Administration (GSA)	2003	In 2006 the GSA mandated that new buildings designed through its Public Buildings Service use BIM in the design stage. GSA has also developed a range of guidelines and standards that includes a National BIM Standard that is internationally recognised.

South America	Brazil/ Strategic Committee for the Implementation of BIM (CE-BIM) and a Technical Support Group (CAT-BIM)	2017	The government aims to make BIM mandatory in Brazil from 2021. The BIM-BR Strategy was developed, covering 9 main points to facilitate adoption throughout the country.
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As governments strive to boost productivity in construction industry, the use of BIM is becoming more prevalent for projects that are currently in planning, and companies that have yet to adopt BIM are increasingly under pressure to do so.

The eco-system (stakeholders): In the construction industry, stakeholders comprised clients, architects, engineers, contractors, suppliers and sub-contractors. Each group has different objectives and interests as well as influences on the success of projects. For the purpose of this study, key stakeholders that will likely impact the PC manufacturers on the use of BIM are as follows; architects, engineers, main contractors, and one of the most influential drivers for pushing companies to use technologies is from the demand of the clients (Lim, 2014).

The company (organisation): The strategy, structure and rivalry within a nation can help organisation sharpen their competitive advantage (Porter, 1990). Their objectives, culture, resources, size of the companies as well as the macro environment will influence the performance of companies. Creating an innovative environment that focussed on developing skilled workforce is essential to sustain competitive advantage (Bew & Underwood, 2010). Regardless of the size of the companies, there must be strong support and commitment from top management for implementing changes to the processes.

A significant group of companies within the PC industry have recognised that IT is vital to their success (Nath et al., 2015; Sacks et al., 2005). With BIM, PC manufacturers involved in design stage can estimate the material costs and manpower accurately. Such technology also helps estimate structural elements, embeds and connections before castings are made. It can also improve information flow and processing. However, there is still a lack of experience and knowledge of BIM, especially in small companies. Furthermore, small companies might still be grappling with costs and economic gains by implementing BIM (Rodgers et al., 2015; Teo et al., 2015).

The team (people): The organisation needs to develop BIM competencies to ensure the implementation of BIM is successful. The capability of its people is one of the critical

elements of the company. For successful transition to BIM, it is essential to select the right team members for the company's initial BIM projects, and the management must ensure adequate time is given. By taking incremental steps, companies will face less resistance from employees (Henderson & Ruikar, 2010). Love et al. (2014) has highlighted an essential criterion, appoint employees with a flexible mind set and willingness to embrace changes. According to Shen et al. (2016) and Bew and Underwood (2010), other aspects to consider are: (1) managing the resistance to change, (2) educating employees and developing BIM expertise, (3) time consideration to make changes, (4) motivation and recognition of efforts, (5) early involvement and buy-in. During the BIM implementation, the management need to properly address these matters to improve their chance of success.

The processes: People and processes are key to change and improvement within organisations. By taking advantage of technologies, companies can leapfrog their businesses in a sustainable manner (Shen et al., 2016). IT has helped to improve productivity; it has also demanded changes in process and communication about stakeholders, in order to maximise the outcomes (Succar, 2009). Common processes among stakeholders must be established to allow collaboration between parties working on construction projects. In practice, collaboration among stakeholders was merely at superficial level (Rodgers et al., 2015). The limited BIM knowledge and experience among stakeholders certainly posted a challenge, especially if project owners have not demanded to use BIM, the collaboration between multi-disciplines was unlikely.

The BIM software tool (technology): considering software packages that meet the PC manufacturers' needs is not a simple process. Many criteria should be considered to make sure that all the companies' needs can be fulfilled. Information exchange, interoperability of BIM software and Industry Foundation Classes were top of the lists in many studies (Migilinskas et al., 2013; Succar, 2009). Other non-technical matters such as availability of local support and cost of ownership were essential (Tulenheim, 2015).

2.1.4 The ranking methods

There is no standardised method or threshold value for identifying CSFs. The mean value or the middle value of a Likert scale is popularly used. For example, Won et al. (2013) suggested selecting those factors whose importance values exceed the total mean value of

each category as CSFs. But this kind of ranking method tends to select almost half of the factors as CSFs. The other widely used methods for determining CSFs are factor analysis and principal component analysis (PCA). The examples are Amuda-Yusuf (2018) and Afolabi et al. (2019). Yet, both factor analysis and PCA are based on the assumption that the data are normally distributed.

In recent years, genetic algorithm (GA) has attracted substantial attention and is widely used in AEC industry. This is because GA can find near-optimal solutions within reasonable computation time and shows flexibility in practical problem solving. It has been commonly deployed for optimization problems (e.g., project scheduling and cost optimisation) and continues to acquire considerable attention among the researchers. However, literature on GA and machine learning is still relatively immature for BIM related studies in the area of productivity, construction management, and sustainability (Darko et al., 2020). In this regard, there is a need to conduct more studies on the application of various machine learning methods and concepts to various AEC problems. Rather than using the traditional ranking methods, this research suggests employing machine learning method like Learn to Rank (LTR) to identify CSFs for BIM adoption.

The genetic algorithm

A genetic algorithm is an iterative and stochastic process that begins with a set of individuals called population (of size φ). Figure 2-3 shows the general working principle of genetic algorithm. GA search from the population for solutions, and if the termination criterion is not satisfied, three different operators are applied to the update population, i.e., selection (or reproduction), crossover and mutation. One iteration (ξ) of these three operators is called a generation. Genetic algorithm mimics the process of natural evolution whereby survival of the fittest is of great importance. In other words, the fittest solution is selected and the unfit is replaced by generations of new individuals (Onwubolu and Babu, 2004). Intuitively, the process will create successive generations of better and better individuals.

Fitness. Every individual in the population is assigned by means of a fitness function, a score. The probability of that individual being selected for reproduction is based on their fitness score.

Selection. The selection operator randomly chooses two individuals from the “mating pool”. The fittest individuals (μ) are selected based on their fitness scores. The higher the score, the better chance to be selected for reproduction.

Crossover. After the two individuals have been selected. GA then calculates if crossover should proceed using a perimeter called the crossover probability (P_c). If crossover does take place, the two individuals are mixed to create an offspring (λ). And the offspring are added to the population.

Mutation. As in nature, mutation occurred during evolution. In GA, the purpose of mutation is to introduce and preserve diversity in the population to avoid premature convergence. The mutation occurrence in GA depends on the mutation probability (P_m) and should be set low (Fernandez-Preto et al., 2012).

Figure 2-3 Working principle of a genetic algorithm. Adapted from Onwubolu and Babu (2004)

GA is inspired by Charles Darwin’s theory of natural evolution. It reflects the process of natural selection where the fittest individuals are selected for reproduction in order to

produce offspring for the next generation. It is a probabilistic optimisation technique ideal for machine learning like LTR.

Learn to rank based on genetic algorithm

LTR is recently a hot research topic in information retrieval (IR) which attracts researchers to develop a number of ranking models to solve it. The goal of IR is given a query to return relevant documents. Two factors are considered for the rank of a document. They are relevance and importance. Hao et al. (2010) computed the connectivity of a web service by a schema tree matching algorithm, and computed its importance using the Complmp algorithm. They then ranked each web service according to the combination of relevance score and importance score. Lin et al. (2012) proposed an improved ranking algorithm with learning features. The learning process usually consists of two steps: training and test. The learning algorithm is input by a training set which is made of query-document pairs. The output is a ranking function which is used to rank the search results for the queries. Furthermore, Ibrahim and Landa-Silva (2018) provided an enhanced evolutionary LTR approach by combining with machine learning.

Although there are many evolutionary LTR approaches in literature (Islam, 2013) their frameworks are all the same: to minimise the distance between the predicted ranking and the input judgment (Niu, et al., 2015). Generally, they fall into three categories: (1) the point-wise approach, (2) the pair-wise approach, and (3) the list-wise approach (Liu, 2009). The point-wise approach treats every single object (query-document pair) as the learning instance. The pair-wise approach views the pair of objects (two query-document pairs for the same query) as the learning instance. And the list-wise approach uses the entire list objects retrieved (the list of query-document pairs for each query) as the learning instance. Previous experiments have demonstrated that the list-wise approaches show better performance in terms of accuracy than the point-wise and pair-wise approaches (Cao et al., 2007).

2.2 The PC supply chain productivity

Fragmentation within the construction industry is well known. It arises predominantly in the traditional construction process, i.e., the construction workflow and practice hinder the integration of construction knowledge among stakeholders. As such, payment problems,

delays, and disputes during the construction phase are all too common (Faridi & El-Sayegh, 2006; Ho & Liu, 2004). Extensive research has been conducted to improve the PC supply chain productivity and efficiency in information tracking, monitoring and sharing. Various technologies, such as BIM and RFID have been deployed to facilitate the implementation of off-site construction. The frequently studied research themes include lean manufacturing and construction (Sacks et al., 2010), precast concrete design (Yuan et al., 2018), construction project management (Arayici et al., 2012), and BIM standards (Nawari, 2012). As far as the PC supply chain is concerned, it was found that the multiple researchers who contributed to PC process primarily focussed on theoretical optimisation (Du et al., 2017; Wang et al., 2018) with simplistic assumptions aimed to achieve a single objective taking only limited consideration to the real-world PC supply chain situation.

2.2.1 The IT usage in the PC supply chain

Although there was a sizable number of studies focussed in inventory management with RFID (Ergen et al., 2007b; Goodrum et al., 2006; Song et al., 2004; Yin et al., 2009), there is still a lag of studies on the automatic identifying, tracking, and locating of PC panels across the PC supply chain (i.e., from production to delivery). In other words, problems still exist in practice, and hinder the productivity of the entire PC supply chain. Below are the key reasons:

- Investigation done by Phang et al. (2019) has shown that majority of the PC manufacturers are at BIM maturity level 0 or level 1. It can also imply the extent of IT usage is low in most construction projects. In other words, traditional approaches still dominate information transmission and collection. This can be inaccurate, inefficient, and error-prone (Zhong, et al., 2017). Such inadequacies hamper timely responses when changes or interruptions occur in the PC supply chain.
- Information resides among the respective stakeholders such as the PC manufacturers, main contractors and customers. This impedes effective coordination and cooperation among the parties, and may cause erroneous inventory tracking, leading to late delivery or even misplacement of PC panels. It has already been identified as a major obstacle to efficiency (Perumal et al., 2010) and could counter the value proposition and advantage of PC construction.

According to the study by Phang et al. (2019), to realise the full potential of IT, the whole ecosystem needs to embrace it, and not just merely the responsibility of a single party. In other words, there should be appropriate technologies, processes and collaborative behaviours between and within organisations, along the supply chain. It requires seamless collaboration across the stakeholders (Li et al., 2014), and the solutions must be well-integrated to realise their full benefits. At the moment, there are two main challenges that may hinder the adoption of these technologies in the PC industry.

1. **Affordability of IT systems:** Implementing IT systems requires high initial outlay as well as subsequent maintenance cost afterwards, this poses a challenge for many SMEs (Ko et al., 2016). As highlighted in the earlier reviews, the late majority and laggards are mostly small companies, which may be due to the affordability of the IT systems. Furthermore, different PC manufacturers differ from each other in operations and usually have different requirements on IT systems. As such, it is challenging for SMEs to obtain bespoke systems to meet with their specific requirements.
2. **Fragmented industry, diverse systems:** In current practice, it is very likely each stakeholder would have implemented different IT system to manage their internal processes. Such standalone systems usually have their specific interfaces and data formats that inevitably leads to information inconsistency which may bring about inefficient communication and hamper collaboration in any the construction project (Ko et al., 2016). In such situation, it is challenging to integrate diverse systems to realise a smooth and continuous cooperative environment for the PC supply chain (Xu, 2011).

The above-mentioned challenges highlight the importance of a common and affordable data environment to improve the productivity of PC supply chain.

2.2.2 The PC pre- and post-production phases

PC pre-production. Significant research has taken place to discuss the factors of delay. Among the many delays, slow shop drawing approval is frequently cited as a major issue. According to Atkins and Simpson (2008), follow up processes cannot commence until the shop drawing is approved by the design team. Furthermore, the coordination of the submittal process depends on the contractual and working relationship, which typically

lacks transparency and reliability (Fisk & Reynolds 2010). Not surprisingly, in a study done by Faridi and El-Sayegh (2006), they have highlighted the approval of shop drawings was among the top ten most significant causes of construction delays. It has not only impacted the success of construction projects, but also the overall economy of a country. Ahmed et al. (2003) attempted to list the various types of delays and the allocation of responsibilities among respective stakeholders. Andi et al. (2010) cited that contractors are slow in the approval of shop drawing and have recommended to put in place a standard operating procedure regulating the time frame for review. Similarly, Alsinaidi (2013) has realised that organisations did not have a basic construction integrated plan on which to have submittal-approval processes and performance measure, a web-based system was proposed to improve communication and visibility. In the study of construction technology on productivity, Marzouk and El-Rasas (2014) have presented a list of delays, and one of the delays caused by consultants was the delay in approving shop drawings.

Despite the many studies on delays and the causes of them, none has given an in-depth consideration and provide real-world solution for improving the approval of drawings process, let alone the PC companies. Such delays may be caused by external parties in the supply chain, such as the owner, consultants, main contractors or sub-contractors. Or internal processes, due to outdated and manual driven information system.

PC post-production. There are many studies focussed on the optimisation of the storage yard. For example, Cheung et al. (2002) proposed using GA to optimise the arrangement of precast yard to minimise the total transport costs. Similarly, Wang and Hu (2017) used GA to modify the traditional production scheduling. While others were focusing on the identification, tracking and locating of PC panels in the storage yard using IT such as RFID and barcodes to distinguish the various components and store critical operation information were studied (Akinci et al., 2003; Goodrum et al., 2006). However, the studies mostly focussed on data gathering and did not thoroughly solve the information communication problems currently encountered by the respective parties in the PC supply chain. In other words, the real-time information has not been made available to the parties involved for on-time decisions making or actions. Furthermore, most studies only investigated the management and tracking of inventory as a singular process. Hence, it becomes imperative to ensure tracking is done across the PC supply chain.

Earlier work done by Hassanein and Nemr (2008) have shown that a database management system was effective in claims analysis and documentation. Such documentation processes for claims and procedure can be managed by means of electronic document management systems. However, there was no provision for internet access, making it ineffective for users and external stakeholders as they are unable to communicate and share information. Ho and Liu (2004) investigated people's behaviour during a potential claim situation. They developed a Claims Decision Model (CDM) based on "game theory" to help project participants better understand by analysing construction claims. A recent study by Abdel-Khalek et al. (2019) has shown that a web-based software provided better document management, field monitoring and time management. Such a system has the ability to view, track and automate progress payment to avoid unnecessary delays. Nevertheless, the use of generic and proprietary software such as Oracle Primavera Contract Management (PCM) is not a viable solution for sub-contractors like PC manufacturers as it does not cater to their specific needs for progress claim process.

Recently, Marzouk et al. (2018) has introduced claim automation and delay analysis methods to minimise the impact of claims in construction projects. This has enabled stakeholders to proactively handle claims by utilising the capabilities of Building Information Modelling (BIM) and visualisation. In another study done by Ali et al. (2020), BIM was utilised to proficiently mitigate the potential disputes among contracting parties due to the extension of time (EOT) claims. The system named BIM-Based Claims Management System (BIM-CMS) was developed to manage EOT claims for different delay events in projects. However, none of these studies aimed at combining the capabilities of BIM and cloud technology to provide centralised database for PC manufacturers to work on and to access claims related information in real-time during the progress claim process.

2.2.3 Lean management in the PC industry

Regardless of the industry, lean is a management philosophy that can help minimise the time, cost, efforts, and wastes as well as maximise the value (Koskela et al., 2002). Lately, lean thinking is one of the most effective methods to improve PC industry efficiency (Li et al., 2014; Nahmens & Ikuma, 2011).

Lean for PC production improvement. Many studies have focussed on optimising the PC production phase through lean approach. Ahmad et al. (2019) discussed the Strategies

to improve the efficiency of the PC production process. Goh and Goh (2019) conducted a simulation study of off-site PC production operations and provided recommendations to improve modular construction efficiency through application of lean concepts. Through a case study approach, Nahmens and Ikuma (2011) attempted to implement lean thinking to improve production operations by eliminating waste.

Lean for PC supply chain productivity improvement. It is also well-recognised that progress visibility of the PC supply chain, component traceability, and information reliability are effective ways for realising lean construction. For instance, Xu et al. (2018) proposed a cloud-based fleet management system to improve the efficiency of the delivery of PC panels. Whereas Li et al. (2014) has developed a digital lean construction platform for companies in the supply chain to collaborate effectively. To improve the communication amongst different phases of PC supply chain, Xiong, et al. (2018) has explored the Process Specification Language (PSL) to unify the process information from multiple planning software applications. It is worth noting that: (1) the company can only reach its full potential with the lean practice when it has fully integrated into the company's culture. Consequently, leadership and coaching to improve every day processes are imperative (Koskela et al., 2002). (2) To improve the leanness of a process, the company can either optimise its operations or building corresponding IT systems or both. Various studies have shown that visibility, traceability, and information integrity are essential for realising lean construction (Wang & Hu, 2017). (3) Existing precast practices are lagging far behind in the adoption of lean management and technologies, therefore extensive works remain to be done (Zhong, et al., 2017).

However, due to the complexities of real-world projects, few studies have done research on the improvement of the overall pre- and post-production phases. As such, extensive work remains to be done from the aspects of shop drawings approval for production, inventory management, and delivery management.

Value stream mapping and analysis (VSM/A). It is one of the most commonly used lean construction tools for the identification of the sources of wastes (Innella et al., 2019). The objective is to document and analyse the present workflow, and tasks are classified into one of the two categories, value-added tasks and non value-added tasks. This allows researchers to transform the present state workflow to future state workflow by either eliminating or optimising those non-value-adding tasks.

Lean construction. It may be attained by eliminating wastage in the following ways (1) eliminate or reduce the time taken for non value-added tasks, (2) reducing the lead time by minimising the number of steps in the process. In order to deal with these non-values added tasks effectively, it is imperative to identify the causes (or origin) of such wastes (Innella et al., 2019; Koskela et al., 2002).

The supply chain lead times are determined by several factors such as: (1) processing time (PT), (2) set-up time (ST), (3) move time (MT) and (4) wait or queue time (WT).

$$\text{Total lead time (TLT)} = \text{Value-added time} + \text{Non value-added time}$$

Or

$$\text{Total lead times (TLT)} = \sum \text{PTs} + \text{STs} + \text{MTs} + \text{WTs}$$

Where,

- Process Time (PT) : the time to fully complete one task and return to the starting point.
- Set-up time (ST) : the time required for changeover of tasks to prepare an operation or process.
- Move time (MT) : the time taken for goods to be moved around, e.g., PC panels
- Wait time (WT) : the time when products or people are idling.

In construction, a substantial amount of time is spent on wait time. During the construction phase, the delay of main contractor decision making to grant an approval for shop drawings is well documented (Faridi & El-Sayegh, 2006). The time taken to make decisions may be critical, especially when different interdependent stakeholders are involved to get a job done. Due to the delay, the downstream stakeholders could take longer than expected time to perform their tasks. Such issue will inevitable impact the performance of the overall supply chain. From the perspective of the PC manufacturer, identifying and eliminating (or at least significantly minimising) such issues can reduce the wait time, and essentially compress lead time. Lead time reduction will enable the PC manufacturer to deliver their PC panels on time, have a better forecast of future demand and fulfilment, and ensure timely progress claim and payment from main contractor.

The study done by Serpell et al. (1995) suggested that wastages can be grouped into two categories - controllable root causes and uncontrollable root causes. As illustrated in Figure 2-4, apart from external factors, all other prevalent causes are controllable. In this research, the author focusses on what the PC manufacturer can control to improve the current key workflows. This will ultimately reduce non value-added tasks and will fulfil one of the core principles of lean concept.

Figure 2-4 Causes of wastes. Adapted from Serpell et al. (1995)

According to Ray et al. (2006), to achieve sustainable results, the following controllable factors (predominantly internal) need to be considered. (1) Management commitment. As with any endeavour, the support and leadership of top management are essential. (2) Learn and change. Lean is about learning and changing through Kaizen (改善). Making small improvements and pacing changes are important to maintain interest and excitement among the team (Innella et al., 2019). (3) Dedicated staff. Lean management requires full-time dedicated staff to champion and facilitate the lean initiative. The common mistake is to assign a manager as part of their duties. (4) Get an experienced lean management consultant, someone who has proven track record in implementing lean practice.

2.3 The information technology in construction

In recent years, the advancement of IT in the construction industry has been broadened as BIM adoption is gaining momentum across the construction industry around the world. As a construction project involves multiple stakeholders, and each stakeholder may be engaged in multiple simultaneous projects; BIM is needed to effectively share information across the value chain. It is transforming and enhancing the workflows in the construction industry.

Project collaboration, as of now, is conducted via a combination of various means and formats. As there are many tools and solutions used in the industry, it has always been a huge challenge to coordinate and maintain up-to-date information. To accommodate a federation of BIM models across software solutions, Industry Foundation Class (IFC), a neutral exchange format was maintained by buildingSMART® (buildingSMART, 2019). Since then, it has gained significant support from BIM software developers and buildingSMART® has constantly maintained IFC to ensure its relevancy.

Either in the proprietary vendors' formats or a neutral format like IFC, BIM information is still stored and transferred in the form of files. As such, the synchronising of a full BIM model can take considerable time and bandwidth especially if wide area network is used. In recent years, cloud technology has emerged as the viable alternative for construction project information to be shared via a series of interfaces and web services. Unlike a file server, it uses the model-driven architecture approach as proposed by the Object Management Group.

Harrison (2009) provides a basic view of the cloud configuration. As illustrated in Figure 2-5, the heart of the system is the BIM cloud which stores all design data pertaining to the projects by collecting information in 2D, 3D or textual format. Users can access these information via applications through web services and interfaces. The greatest differences from file-based sharing are: (1) all stakeholders have access and are working on a single master model, while ensuring they are working on the latest version. Significantly, users can read from and write to the same digital model. (2) Real-time collaboration is possible as the data are centrally kept centrally in the database and refreshed from the BIM cloud, and (3) it offers workload sharing of large projects among users.

There are many studies that deploy the Internet of Things (IoT) and cloud computing in the construction industry. However, most of the earlier studies have focussed on the traditional cast-in-situ construction process or specific phases of construction projects, which cannot be effectively applied to the PC supply chain (Ko et al., 2016; Riaz et al., 2014; Zhou et al., 2018). The following sections discuss the relevant and available technologies that may be applied to real-world PC supply chain environment.

Figure 2-5 Overview of a cloud configuration. Adapted from Harrison (2009)

2.3.1 BIM cloud technology

The U.S. National Institute of Standards and Technology defined cloud computing as “a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction” (Mell & Grance, 2011).

BIM cloud for the PC industry: in the fragmented construction industry, projects typically involve a vast array of software solutions across the respective stakeholders. In addition, the cost of upgrading their IT infrastructures and finding BIM talents become a burden to PC manufacturers, in particularly the small enterprises (Ko et al., 2016). As the industry gradually moves towards cloud services, it should help address many of these issues mentioned above by providing access to information by various applications and users. However, in Singapore the adoption and usage of BIM cloud in the construction sector is still rather low.

With the introduction of cloud computing, the BIM software package and project management applications can reside in the cloud, which opens a wide range of new functions and possibilities. The deployment of cloud computing with BIM technology involves BIM application, which is purpose-built for the construction industry to effectively access critical information to make timely decisions. By means of desktop computer or mobile devices (such as smartphones or tablets), stakeholders are allowed to view, comment or even edit the BIM models anywhere and anytime, without the need to

install specific software (Zhang et al., 2010). Figure 2-6 provides an example of BIM cloud configuration.

Figure 2-6 Overview of BIM cloud collaboration platform

The tracking process of the precast components starts at the PC factory. It allows information to be shared via the BIM cloud and the status of the construction is updated in real-time from the construction site. The key benefit of the BIM cloud is to facilitate dynamic, bidirectional communication between sites. For the purpose of this research, the BIM cloud must provide the following features:

1. **Multi-tenancy:** in a multi-tenancy environment, services offered by different application providers reside in a single hosting infrastructure. Multiple users can share the same application, running on the cloud, possible on the same hardware and same data-storage. However, users will not have access or share each other's data (Zhang et al., 2010).
2. **Interoperation among applications:** BIM cloud to function at its full potential, applications must connect with each one to allow data exchange among them (Kumar et al., 2010). Without which, federated models coming from different discipline will not be able to be combined.

3. Geo-distribution and ubiquitous access: cloud computing enable anywhere, anytime access by any device such as mobile phone, tablets or desktop computers. Hence, to provide high service level quality, geo-diversity (i.e., data centres located across the globe) is essential (Zhang et al., 2010).
4. Visualisation and manipulation: by providing the visualisation capability, BIM cloud can present key information on the status of the project via the 3D BIM model. Besides, it also allows manipulation of information (such as pan or zoom function) for users at anytime and anywhere (Chuang et al., 2011).
5. Information access: according to the study done by Kumar et al. (2010), cloud computing enables information sharing for the construction industry. And it may even accelerate the adoption of construction IT, due to the affordable pricing model of BIM cloud. Such practices allows informed decisions making throughout the project's lifecycle.
6. Affordable pricing: it will attract more construction companies to embrace BIM cloud. For example, (Zhang et al., 2010) discussed about utility-based pricing and providing on-demand services. Nevertheless, the pricing model will depend on the different application vendors.
7. Remote viewing: It facilitates remote viewing and distribution of information by means of a web browser. Users are able to access and use applications on the cloud as well as share of information without additional software installed in the computer (Chuang et al., 2011). This opens up a new dimension of possibilities for project management by allowing stakeholders to keep track of the work and progress of projects real-time.
8. Drawing annotation: the mark-up feature is available to allow users to view drawings through the cloud, and also to mark the drawings with notes and annotations. Besides, alerts in the form of email or text messages could be sent to the relevant parties to view the updates.
9. Drawing management: It enables users to view and edit the documents in the cloud. Such features allow viewing of multiple models in the same geometric space at the same time.

2.3.2 Visualisation technology

According to a research done by Kernbach et al. (2015), the use of visualisation was better than the use of text in the communication of ideas. In other words, visualisation is significantly better in terms of achieving attention, agreement, and retention. In fact, visualisation provides a common language for all parties involved, and the proper use of visualisation techniques is an important contributor to the improvement of project communication and coordination (Al-Kodmany, 1999). There are three key advantage of utilising visualisation systems for monitoring of data: (1) effective data presentation at any given time on BIM cloud, (2) criteria-based review, and (3) facilitate time-based progress evaluation.

1. **Effective data presentation at any given time on BIM cloud.** In a 3D environment, the positional information is presented by displaying its location. And by means of a viewer, it allows for the direct and easy visual comparison of the respective PC panels and their status by using a colour coding technique. For instance, individuals often associate the colour red with unfavourable situations and green with favourable conditions. Thus, stakeholders can immediately understand the project status simply by recognising the colours so that actions can be taken accordingly. Figure 2-7 shows a screenshot of a building project in full 3D presentation.

Figure 2-7 Full 3D presentation of a building project

This is a huge different from static presentation (e.g., bar charts or text display). While charts and text displays are probably the only way to convey exact readings to viewers, both cannot provide visual comparison. Furthermore, conventional methods like charts

and numbers clutter the display if mobile devices are used, making information difficult to see. On the other hand, a 3D display can help viewers condense large amount of information.

2. **Criteria-based review.** As the complexity of the building project increases, it becomes challenging to identify areas that need immediate attention even if 3D presentation is used. Therefore, it is necessary to ensure that users can filter out information based on a set criteria. One effective technique is to display only data points that meet user specification. The visualisation system allows data to display based on the floor level as requested by users. Such an approach helps filter out unnecessary data, which can be otherwise difficult to comprehend when too much information is displayed on-screen. Figure 2-8 displays the selected floor, showing the completion status based on the colour coding technique. In this case, PC panels are displayed in different colours, representing the different status, e.g., in-transition or installed on site.

Figure 2-8 Selected view presentation of a building project

Similarly, the section plane's function allow user to cut the 3D model along a plane so that user can focus on the information provided by the active section plane and hide everything else as shown in Figure 2-9. This function is extremely useful when working with large models. Users can zoom in to check the status of a specific section or make a screenshot for a presentation.

Figure 2-9 Selected view by section plane

3. **Facilitate time-based progress evaluation.** During the construction phase, the status changes over time. The capability of using animation to view the progress of the project offer additional help to the stakeholders. They can review the activities over a specified period that conventional charting has limited capability to provide. The visualisation system can display a 24-hour clock plot that shows the data variations as specified by users. This approach can easily show activities for an extended time period, and users can adjust the period accordingly, to help them focus on certain performance measurements. Time animation is useful to monitor long-term activity by presenting a collection of data to users. They can specify the length of time to monitor status change within that time period and may wish to take necessary actions to investigate further when needed. Since all information is displayed in 3D, users can change the viewpoints or zoom into their area of interest depending on the questions at hand.

2.4 Summary

The first step is to conduct a critical literature review to evaluate the existing body of knowledge relating to BIM adoption. However, there is hardly a mention of the critical success factors (CSFs) that can help transform PC manufacturers through BIM adoption. As such, the author proceeded to examine previous studies pertaining to technology adoption models, the key drivers that influence BIM adoption, previous proposed CSFs for BIM adoption as well as the ranking methods.

Many studies have focussed on improving PC supply chain productivity and efficiency in information tracking, monitoring and sharing. However, none has given any consideration

and provision of real-world solutions for improving the pre-production and post-production phases of PC manufacturer. (1) The studies on factors of delay were mostly focussed on data collection and did not thoroughly solve the pertinent problems. Besides, there was no research focus on improving key pre-production process such as shop drawing approval for production. (2) The studies on the automatic identifying, tracking and locating of PC panels at storage yard or in delivery only investigated the management and tracking of inventory as a singular process, their foci were mainly on data gathering and did not thoroughly solve the information communication problems encountered by the key parties across the PC supply chain. (3) The current studies on claim and payment were mostly focussed on standalone solutions which targeted at general constructors' usage. There is currently no study that aims at addressing the PC manufacturers' challenges in progress claim and payment. (4) The current studies on lean management predominantly focussed on improving the efficiency of production operations during the precast production phase. To bring about a sustainable improvement to the entire PC supply chain, key workflows in the pre- and post-production phase need to be examined and addressed.

As far as IT in the construction industry is concerned, previous studies have focussed on the traditional cast-in-situ construction process or specific phases of construction projects, which cannot be effectively applied to the PC supply chain. Nevertheless, relevant and available technologies such as BIM cloud and visualisation technology can be applied to provide real-world solutions to the PC manufacturers and their supply chain.

Chapter 3 : Research methodology and data collection

This chapter discusses the research design which is influenced by the nature of a research topic and objectives. The choices of research methods and the associated research tasks are explained. Generally, this research involves both qualitative and quantitative research methods. Primary data were collected throughout the entire study.

3.1 Overview of research design

The research design is highly influenced by the research objectives. As indicated in Figure 3-1, a total of seven tasks were needed to achieve the entire research objectives.

To establish a conceptual BIM adoption model for PC manufacturers, task 1 was to conduct an in-depth review of the BIM adoption in AEC industries, the various adoption models, the key drivers and critical success factors for BIM adoption and the ranking methods. To determine the CSFs for BIM adoption among the PC manufacturers, a new PCBIM hexagon framework was proposed to help design the survey questions. After the initial review and exploratory study, a questionnaire survey was conducted to determine the CSFs (Task 2). To assess and shortlist the CSFs that directly contribute to productivity improvement, hypotheses were formulated and multiple regression was conducted (Task 3). A model called “PC-CSF performance analytical model” was then established to assist PC manufacturers navigate towards higher levels of productivity.

To determine the usefulness of the PC-CSF performance analytical model in real-world scenarios. It was necessary to select a suitable PC manufacturer that provides the conditions under which the application of the PC-CSF performance factors can be made. A review of existing literatures on the PC supply chain productivity, information technology in construction as well as the lean management was conducted (Task 4), in order to situate this study in relation to existing body of knowledge. Interviews with subject-matter-experts were carried out to identify and gain insights into the current PC supply chain processes, practices and issues (Task 5). Key workflows in the PC supply chain were identified as case studies. To support the application PC-CSF performance factors on the case studies, purpose-built BIM cloud-enabled systems were developed (Task 6). Finally, in Task 7, productivity improvement brought about by the combined benefits of the PC-CSF performance factors was measured.

Figure 3-1 Illustration of research framework

3.2 Determine the CSFs affecting BIM adoption of PC manufacturers

This part of the study adopted a quantitative research method to realise the status of BIM adoption among the PC manufacturers. As indicated in Figure 3-2, a total of six steps were needed to achieve the first two research objectives. Namely, (1) to establish a BIM adoption model from the perspectives of PC manufacturers to explain organisations' BIM adoption status and (2) to develop the PCBIM hexagon framework for the determination of the CSFs affecting BIM adoption.

Figure 3-2 Research workflow to determine CSFs for BIM adoption.

Referring to Figure 3-2, Step 1 was to conduct an in-depth literatures review of the BIM adoption in AEC industries, the various adoption models, the key drivers and critical success factors for BIM adoption and the ranking methods. Step 2 was to establish conceptual BIM adoption model for PC manufacturers to navigate towards higher levels of technology utilisation. Section 3.2.1 explains the conceptual BIM adoption model.

To identify the CSFs for BIM adoption among the PC manufacturers, a PCBIM hexagon framework was proposed. It consists of driving forces from six areas: government, eco-system, company, team, process and BIM software tool. Accordingly, the questionnaire was derived from the framework (Step 3). Section 3.2.2 discusses the development of the PCBIM Hexagon framework.

The questionnaire was sent out to the respective PC manufacturers (Step 4). The survey and data collection efforts were clearly explained in section 3.2.3 and 3.2.4. To identify the CSFs for BIM adoption, Step 5 was to analyse the data collected from the survey, which is presented in section 4.1.

3.2.1 Establishment of the conceptual BIM adoption model

The author proposes a BIM adoption model from the perspectives of PC manufacturers to explain organisations' BIM adoption status and furthermore, to identify the CSFs that affect their successful BIM adoption. The proposed model combines BIM maturity statuses and key actor features into a grid chart, as depicted in Figure 3-3.

Figure 3-3 A conceptual model of BIM adoption

There are three moving directions from one grid to another: X-direction, Y-direction, and XY-direction (the upward diagonal direction). Take a PC manufacturer in the grid of “Group 0 Level 0” as an illustration. It can upgrade to the neighbouring grid of “Group 0

Level 1” following the X-direction to the grid of “Group 1 Level 0” following the Y-direction or the grid of “Group 1 Level 1” following the XY-direction. Of course, moving directly to the grid of “Group 1 Level 1” is mostly desired. Thus the XY-direction among all the three directions is the ideal transition direction to a PC manufacturer in the chart. The move can be driven by both internal and external forces. Although, there are many affecting factors that can facilitate the companies in terms of BIM adoption to some extent, by placing the emphasis on CSFs, the companies may have a tendency to jump in the grid chart towards the highest level of technology adoption in the fastest rate, i.e., following the XY-direction.

3.2.2 Development of the PCBIM Hexagon framework

As presented in section 2.1.3, there is a large body of literature dedicated to surveying key drivers for BIM adoption and can be summarised as follow. The literature review has shown that governments strive to boost productivity in construction industry and the adoption of IT (e.g., BIM) is essential to productivity improvement. As such, they have provided the necessary strategies, supports and guidelines to promote BIM adoption. Pressures from the eco-system have also played a pivotal role. For instance, client demand has significantly driven BIM uptake and architects, engineers as well as general contractors are usually the most influential drivers.

A significant group of companies within the PC industry have recognised that IT tools such as BIM is vital to their success. However, for successful transition to BIM, it is essential to select and nurture the right team members to start the company’s BIM journey on the right footing. However, IT has also demanded changes in the process and coordination with stakeholders in order to maximise the outcomes. As far as the BIM tool is concerned, many criteria should be considered to make sure that all the companies’ needs can be fulfilled. As illustrated in Figure 3-4, the author hereby proposes a conceptual framework and has named it “PCBIM Hexagon” to summarise these forces which are from the six key areas: (1) government, (2) eco-system, (3) company, (4) team (people), (5) process, and (6) tool (technology). Accordingly, the questionnaires were derived from the framework.

Figure 3-4 PCBIM Hexagon: BIM framework for PC manufacturers

To this end, the following were created (1) a BIM adoption model which is a mix of a BIM maturity model and a BIM adopters' model and acted on by the driving forces; and (2) a PCBIM hexagon framework consisting of driving forces from six areas: government, eco-system, company, team, process and a BIM software tool.

3.2.3 Determination of CSFs for BIM adoption

Based on the developed PCBIM Hexagon, the design procedure of the survey questions was as follows. The initial list of the questions was created by the author through a review of the extant literature. The author then conducted one-on-one interviews with three BIM experts from medium and large sized PC manufacturers in Singapore. After their replies were studied, an interview session was then arranged with each company to allow respondents to further clarify and express their opinions. Sample comments came from one of the PC experts as shown Table 3-1.

Table 3-1 Sample comments from a PC expert

Key area	Questions asked	Comments from PC manufacturers
Process: Design phase	Were PC manufacturers invited early to take part and contribute in design stage?	The main problem we face is that BIM model from main contractors are not finalised and coordinated early enough. One reason is that most works are outsourced, and another reason is that sub-cons are not on board early stage of the process. This caused

		tremendously delay and inaccuracy in the 3D model and is often good for reference only.
Process: Production phase	How often do changes occur and when will it stop?	Drawings production can be faster if changes are well controlled and hence shorten the time during design stage. In almost every project, changes continue until the last panel is cast.

The experts were encouraged to propose any questions which they deemed pertinent to this study. After the questionnaire was drafted, it was sent back to the experts for further review. Through an iterative process, the author and the interviewed experts reached a consensus, and the 25 most important questions were shortlisted. The final questionnaire thus was determined and ready to be fielded

Then, questionnaire was sent out to the PC manufacturers. Most of the surveyed companies in this study are based in Singapore. In a continuous effort to promote precast concrete for affordable housing, Singapore is now also known globally as one of the leading countries in precast practices. In addition, PC manufacturers in other countries including many ASEAN countries and some European countries were also invited for this survey depending on the author's familiarity with them. The invitation to a web-based questionnaire was sent to the targeted group via email.

The questionnaire comprised two parts. The first part was designed to collect fundamental information regarding to the respondents' company size, type of PC projects and operational details (e.g., years of operation, factory's location and so on). Additional information pertaining to the current BIM utilisation and expectation were also obtained. Such data are essential to ascertain their BIM adoption status, as well as the perceived benefits relating to productivity and collaboration (as shown in Table 3-2). The second part (as shown in Table 3-3) was made of the targeted questions.

Table 3-2 Portion of the first part survey questions

	Areas	Code	Questions
PC	BIM utilisation and expectation	PC1	The company uses BIM models to extract bill of quantities for material purchasing and tendering
		PC2	The company uses BIM for productivity improvement
		PC3	The company use BIM models to convey design intent, enhance communication and coordination among stakeholders
		PC4	The company does not use BIM

Table 3-3 Second part survey questions

	Areas	Code	Questions
A	Government and market forces	A1	Government policies and support on BIM implementation in precast sector
		A2	Pressure from other precast companies
		A3	Demand from the eco-system to use BIM for better collaboration, i.e., clients request for BIM
		A4	Enhance company reputation through the use of new technologies like BIM
		A5	BIM to be used as a competitive advantage
B	Company	B1	The persistent commitment of top management on BIM adoption
		B2	BIM training roadmap to build BIM capabilities at different level, i.e., from management of BIM users
		B3	Company willingness to change of workflows
		B4	Setting up a BIM committee to help steer BIM implementation in the company
		B5	Dedicated BIM department/team that supports all BIM requests
C	Team	C1	Finding employees with BIM modelling skill set
		C2	Getting people to understand the potential and value of BIM over 2D drafting
		C3	Give adequate time and bandwidth to the team members during the transition phase to BIM
		C4	Early involvement of team members to build strategies for change, i.e., get early buy-in of team
		C5	Certification in BIM for precast to assess individual understanding of BIM
D	Process	D1	In a typical project, the precast design intent is discussed at the initial design stage, including design of precast structures and precast connections
		D2	BIM models provided by structural engineers contain sufficient and accurate information, i.e., for further processing
		D3	Data extracted from the BIM models improve productivity
		D4	BIM models interface with Enterprise Resource Planning (ERP) system
		D5	Drawing production can be faster if changes are well controlled and hence shorten production time
E	BIM software tool	E1	The simplicity (the ease of modelling with libraries support) of use
		E2	The interoperability of the BIM software with other applications and machinery
		E3	The customisability of the BIM software to address the requirements of every precast companies
		E4	The reputation of BIM software, i.e., well known for successful engagement with precast companies
		E5	The availability of local support team, i.e., BIM software vendors timely technical support

3.2.4 Collection of data from survey

The survey was conducted over a period of six months. To improve the response rate, three weeks after the initial survey was sent, a follow-up reminder was emailed to those who had not responded. Moreover, many phone calls were made to non-respondents in the last two weeks before the survey period ended. Sometimes additional personal invitations were also

made in order to increase the response rate. Section 4.1 provides the analysis and discuss of the data collected from the survey. Appendix B presents the raw survey data.

3.3 Identification of CSFs contributing to productivity improvement

Realising the CSFs for BIM adoption can certainly facilitate PC manufacturers towards higher levels of technology utilisation. The third research objective is to assess and identify the CSFs that bring about productivity improvement to the PC manufacturers. To achieve this research objective, the following three steps were taken as shown in Figure 3-5.

Step 1 was to express the identified CSFs for BIM adoption (section 4.1.3 presents the identified CSFs) into constructs to explain a given statement in the questionnaire. For instance, “B1 - The persistent commitment of top management on BIM adoption” can be clearly understood and explained using “top management commitment”. By using the CSFs of the BIM adoption as predictor variables to predict the outcome of PC2 (i.e., the company uses BIM for productivity improvement as dependent variable, the hypotheses were then formulated (Step 2). Data of PC2 was obtained during the first part of the survey (see Table 3-2) and finally in Step 3, to test of the hypotheses, multiple regression was then conducted to identify CSFs that directly contribute to productivity improvement of the PC manufacturers.

Figure 3-5 Research workflow to identify CSFs for productivity improvement

3.3.1 Hypotheses H₁ to H₈ formulation

Firstly, the author has expressed the statement of the each identified CSF for BIM adoption and with the corresponding construct that can be easily understood. Table 3-4 summarises evidence from previous studies supporting those relationship.

Table 3-4 Summary of variables

Construct	Code	Dependent variable statement	Reference
Productivity improvement	PC2	The company uses BIM for productivity improvement	Du et al. (2017); Lim (2014); Nawari (2012); Sacks et al. (2010); Yuan et al. (2018); Wang et al. (2018).
Construct	Code	Predictor variables statement	Reference
Government policies	A1	Government policies and support on BIM implementation in precast sector	Lim (2014); Porter (1990).
Competitive advantage	A5	BIM to be used as a competitive advantage	Bew and Underwood (2010); Porter (1990);
Top management commitment	B1	The persistent commitment of top management on BIM adoption	Ahire and Ravichandran (2001); Henderson and Ruikar (2010); Liang et al. (2007); Shen et al. (2016); Srivastava (1983).
Team coordination	D1	In a typical project, the precast design intent is discussed at the initial design stage, including design of precast structures and precast connections	Brannick (1997); Eadie et al. (2015); Hong et al. (2018; Wang & Leite (2012).
Information sharing	D2	BIM models provided by structural engineers contain sufficient and accurate information, i.e., for further processing	Koçoglu et al. (2011); Nath and Standing (2010).
Constructible BIM	D3	Data extracted from the BIM models improve productivity	Migilinskas et al. (2013); Nath et al. (2015); Sacks et al. (2005); Spitler et al. (2015).
Drawing approval	D5	Drawing production can be faster if changes are well-controlled and hence shorten production time	Andi et al. (2010); Atkins and Simpson (2008); Fisk and Reynolds (2010); Marzouk and El-Rasas (2014).
Local support	E5	The availability of local support team, i.e., BIM software vendors timely technical support	Tulenheimo (2015).

Secondly, the following hypotheses were formulated:

According to Porter's Diamond model (Porter, 1990), governments provide the technology adoption strategies; establish the necessary guidelines, policies and mandates as well as investing in capabilities and capacities of the workforce. They can motivate companies to adopt and use technologies to improve productivity by granting subsidies or other financial incentives (BCA, Technology Adoption: Building Information Model (BIM) Fund V2,

2015). Furthermore, government can make efforts in creating an effective environment for construction innovation (Lim, 2014). Thus,

H₁: The Government policies (A1) positively impact the productivity of the PC manufacturers.

The strategy, structure and rivalry within a nation can help organisation sharpen their competitive advantage (Porter, 1990). Furthermore, creating an innovative environment that focussed on developing skilled workforce is essential to sustain competitive advantage (Bew & Underwood, 2010), which ultimately led to productivity gain. Thus,

H₂: The BIM competitive advantage (A5) improves the productivity of PC manufacturers.

The top management behaviour and actions performed to facilitate technology diffusion is essential (Ahire and Ravichandran, 2001). This encourages employees to adapt a new IT and workflows toward specific goals (Ba et al. 2001) and also helps in implementing changes to the processes. Top management can take incremental steps and adjust the necessary levers to motivate, educate and obtain buy-in from employees (Henderson & Ruikar, 2010; Shen et al., 2016). This ultimately brings companies to higher level of productivity (Srivastava, 1983). As such, the following hypothesis was formulated,

H₃: The top management commitment (B1) improves the productivity of PC manufacturers.

According to Wang and Leita (2017), the purpose of team coordination meeting among project participants is to minimise conflicts between trades and help improve productivity across projects. As far as project team coordination is concerned, a unified approach to project management should be implemented, rather than dividing the project work into different silo of works (Eadie et al., 2015). In other words, team coordination minimise re-work, leading to productivity improvement in construction projects (Hong et al., 2018). As such, a hypothesis was formulated.

H₄: Team coordination (D1) in the organisation improves the productivity of PC manufacturers.

Information sharing is a key strategy that leads to cost reduction and improve the underpin relationship among project participants (Nath & Standing, 2010). According to Koçoglu et al. (2011), information sharing enhance productivity by improving partnerships among project participants, enable faster delivery, improve order fulfilment rate and facilitate the achievement of competitive advantage. As such, a hypothesis was formulated.

H₅: Information sharing (D2) across different departments improves the productivity of PC manufacturers.

A significant group of companies within the PC industry have recognised that the utilisation of IT, such as BIM is vital to their success (Nath et al., 2015; Sacks et al., 2005). According to Migilinskas et al. (2013), the detail information and data obtained from BIM have brought about productivity to project participants. Thus,

H₆: The utilisation of constructible BIM (D3) improves the productivity of PC manufacturers.

Significant research has taken place to discuss the factors of delay. Among the many delays, slow shop drawing approval is frequently cited as a major issue (Atkins & Simpson, 2008; Fisk & Reynolds, 2010). Andi et al. (2010) cited that contractors are slow in the approval of shop drawing, where else Marzouk and El-Rasas (2014) pointed the delays to consultants. Regardless of its origin, shop drawing delays negatively impact productivity (Fulford & Standing, 2014). As such, a hypothesis was formulated.

H₇: Faster drawing approval (D5) improving productivity of PC manufacturers.

According to Tulenheimo (2015), among many challenges during BIM usage, non-technical matters such as availability of local support was an essential consideration. Unless BIM experience users are readily available in the company, the lack of local support may lead to degradation of BIM knowledge and skills in using BIM. This, in turn, impacts productivity when used on projects.

H₈: The availability of local support (E5) from BIM software vendors improves productivity.

Table 3-5 provides a summary of the eight hypotheses.

Table 3-5 Summary of the eight hypotheses

Parameters	Respective Hypothesis	
A1 → PC2	H ₁	The Government policies (A1) positively impact the productivity of the PC manufacturers
A5 → PC2	H ₂	The BIM competitive advantage (A5) improves the productivity of PC manufacturers
B1 → PC2	H ₃	The top management commitment (B1) improves the productivity of PC manufacturers.
D1 → PC2	H ₄	Team coordination (D1) in the organisation improves the productivity of PC manufacturers.
D2 → PC2	H ₅	Information sharing (D2) across different departments improves the productivity of PC manufacturers.
D3 → PC2	H ₆	The utilisation of constructible BIM (D3) improves the productivity of the PC manufacturers.
D5 → PC2	H ₇	Faster drawing approval (D5) improving productivity of the PC manufacturers.
E5 → PC2	H ₈	The availability of local support (E5) from BIM software vendors improves productivity.

3.3.2 Testing of the eight hypotheses

To test the above hypotheses, multiple regression was then conducted. By using the identified CSFs for BIM adoption as predictor variables to predict the outcome of PC2 (i.e., the company uses BIM for productivity improvement) as dependent variable, the author may determine whether these CSFs have effect on productivity improvement for PC manufacturers. Based on the regression analysis, the CSFs that contribute directly to productivity improvement will be obtained and the author called those factors the “PC-CSF performance factors”.

Multiple regression was preferred for the following reasons, (1) it has a more predictive power than the popular structural equation modelling (SEM) and is more suited for exploratory research. (2) It is suitable for smaller sample size, at least 30 cases (Gefen et al., 2000). In this study, the sample size is 53. Multiple linear regression (also known as multiple regression) is a linear approach to modelling the relationship between a dependent variable (denoted by y) and two or more predictor variables or independent variables (Freedman, 2009). The general multiple regression model is:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots \beta_{k-1} x_{k-1} + \beta_k x_k + \epsilon$$

Where:

- y, the dependent variable;
- x_1 , the first predictor variable;
- x_2 , the second predictor variable;
- x_k , the “k” predictor variable; and
- ϵ , the residual error, which is an unmeasured variable.

The parameters in the model are:

- β_0 , the Y-intercept;
- β_1 , the first regression coefficient; and
- β_2 , the second regression coefficient.
- β_k , the “k” regression coefficient.

The response y depends on several predictor variables $x_1, \dots, x_k$.

According to Freedman (2009), a typical multiple regression equation will have an intercept (β_0) and several predictor variables. The value of the regression coefficient β_1 to β_k signifies how much the dependent variable changes given a one-unit shift in the independent variable while holding other variables constant. In matrix form, we rewrite the model as

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix} = \begin{bmatrix} 1 & x_{1,1} & x_{1,2} & \dots & x_{1,k} \\ 1 & x_{2,1} & x_{2,2} & \dots & x_{2,k} \\ \vdots & \vdots & \vdots & \dots & \vdots \\ 1 & x_{n,1} & x_{n,2} & \dots & x_{n,k} \end{bmatrix} \times \begin{bmatrix} \beta_0 \\ \beta_1 \\ \beta_2 \\ \vdots \\ \beta_k \end{bmatrix} + \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \vdots \\ \epsilon_n \end{bmatrix}$$

$$Y = X \times \beta + \epsilon$$

The least squared estimator for the multivariate regression linear model in matrix form called Ordinary Least Squared (OLS) estimator is shown below, where $\hat{\beta}$ is the estimate of β and X' is the inverse of X .

$$\hat{\beta} = (X'X)^{-1}X'Y$$

The regression output will usually include an F-test, and if the F is significant, that often suggest the model is valid (Freedman, 2009).

Section 4.1.4 presents the results of the hypotheses testing and the PC-CSF performance factors.

3.4 Determine the usefulness of the combined PC-CSF performance factors in the PC supply chain

This part of the study to test the hypothesis and at the same time, determine the usefulness of the PC-CSF performance factors in real-world scenarios. It addresses the fourth and fifth research objectives, i.e., (1) To demonstrate and validate these factors are useful for the PC manufacturer and its supply chain and (2) to analyse and present the productivity improvement data across the identified key workflows in the PC supply chain.

Figure 3-6 Research workflow to determine the usefulness of PC-CSF performance factors

As indicated in Figure 3-6, once the PC-CSF performance factors were obtained, the hypothesis was formulated to determine if they could improve the productivity of key workflows in the PC supply chain (Step 1). The author has proposed to apply the PC-CSF performance factors to the key PC supply chain workflows for reasons as described in section 3.4.1. The PC-CSF performance factors were translated to actionable items so that the author may take specific actions to test the hypothesis (Step 2). Step 3 is to determine the case studies to test the hypothesis and demonstrate the combined benefits and implication of the PC-CSF performance factors. With the strong backing from top management, interviews were then conducted with subject-matter experts to identify and

gain insights into the current practices and issues of the current workflows in the PC supply chain.

The development of BIM cloud-enabled system with lean thinking was done to support the PC-CSF performance factors in transforming the current workflows (Step 4). Step 5 was to apply the PC-CSF performance factors to the identified key PC supply chain workflows as described in section 3.4.5. Step 6 was to compare and analyse the results between the current and newly developed workflows. And finally in Step 7, depending on the results of the study, the hypothesis would be either accepted or rejected. The following sections discuss each step in detail.

3.4.1 Hypothesis H₉ formulation

Due to the fragmented nature of the construction industry, the current practice with most supply chain stakeholders would be to implement different system to manage their internal processes. Such standalone systems inevitably leads to information inconsistency which may negatively impact productivity in any construction projects (Ko et al., 2016; Phang et al., 2019; Xiong et al., 2018). According to Nath and Standing (2010), productivity in the supply chain will not improve unless its workflows are optimised and well connected. Based on the research done by Thomas and Tang (2010), sub-contractors like PC manufacturers need to focus on improving critical workflows such as approval of drawings and payment. Slow decision making and constant design changes by others can have detrimental effect on their productivity and any delay in payment can create cash flow bottleneck. As such, this study proposes to apply the combined benefits of the PC-CSF performance factors to improve the key workflows in the PC supply chain.

Furthermore, to realise the full potential of BIM, the ecosystem needs to embrace it, and not just merely the responsibility of the PC manufacturers. BIM must be utilised in key workflows, so that the whole ecosystem can benefit from it (Arunkumar et al., 2018; Liao et al., 2017; Phang et al., 2019).

In general, team coordination and information sharing among project stakeholders are lacking in construction supply chain, thereby impacting productivity (Khalfan et al., 2002;

Koçoglu et al., 2011; Liu et al., 2017; Zhang et al., 2017). As such, the transformative capabilities of the PC-CSF performance factors should bring about productivity improvement to the key workflow in the PC supply chain. Clearly, IT has a pivotal role in information sharing and help improve productivity by reducing delays and other problems; however, it also demands changes to the processes with stakeholders in order to maximise the outcomes (Succar, 2009).

The top management commitment from stakeholders is essential for successful completion of any project (Iyer and Jha, 2005). According to Rami Huges (2014), top management has significant effect on productivity across the supply chain. They can take necessary steps and adjustment to motivate, educate and obtain buy-in from employees (Henderson & Ruikar, 2010; Shen et al., 2016), thereby leading the company to higher levels of productivity. In this study, the author worked closely with the top management of PC manufacturers and the main contractor to ensure sufficient supports were given by the respective departments.

Thus, to positively impact the identified key workflows in the PC supply chain, the following hypothesis was formulated:

H₉: The combined benefits of the PC-CSF performance factors could greatly improve the productivity of key workflows in the PC supply chain.

The author will first translate the PC-CSF performance factors into actionable items, determine key workflows in the PC supply chain and then apply the PC-CSF performance factors collectively to the identified workflows. The results will determine if we should accept or reject hypothesis H₉.

3.4.2 Translate the PC-CSF performance factors into actionable items

For the purpose of this study, the PC-CSF performance factors needed to be ‘operationalised’ to match with empirical data (Campbell, 1975). As such, the PC-CSF performance factors have been translated to actionable (or operational) items so that the author may take specific actions with the identified workflows to test hypothesis H₉ and demonstrate the factors’ usefulness.

To avoid or minimise any participant and researcher biases, the scopes and the actionable items of each factor were primarily derived from past studies together with the feedbacks obtained from subject-matter-experts of the selected PC manufacturer. For instance, to determine the scope and derive actionable items for “team coordination”, related literature about team coordination in construction industry was reviewed. Multiple meetings were then conducted with individuals who engage with cross-department or cross-organisation coordination (e.g. planning coordinators). Probing questions were used during the one-to-one interviews with the respective parties, i.e., “others have mentioned that...” or “any more to add?”. This is to ensure the author can re-evaluate impressions or cross check on assumptions about the topic. Finally, the actionable items pertaining to “team coordination” were derived. Table 3-6 presents the actionable items to be implemented for productivity improvement of the current workflows. Section 4.1.4 provides detail discussion of the PC-CSF performance factors.

Table 3-6 Translating the PC-CSF performance factors into actionable items

No.	PC-CSF performance factors	Code	Predictor variable statement	Scopes	Actionable items
1	Constructible BIM	D3	Data extracted from the BIM models improve productivity	<p>Constructible BIM may be summarised as follow:</p> <ol style="list-style-type: none"> 1. BIM can be used to verify construction flows such as design, components, space, and connecting works (Koskela, 2000). 2. Each element must be modelled with thought towards installation sequence and the characteristics of the physical fabrication. i.e., the form and location of the digital representation must accurately represent that of the physical fabrication (Spitler et al. 2015). 3. The physical fabrication can be placed in the location of the digital representation. The modelled assemblies surrounding the digital element must accurately represent that of the existing condition of the building (Spitler et al. 2015). 4. BIM model with level of development (LOD) 400. It includes complete fabrication, assembly and detailing information such as quantity, size, shape, location and other essential details (BIMForum, 2019). 	<p>A constructible BIM model with full details to address any precast fabrication issues such as consideration on lifting position, maximum transportation weight and size, penalisation, and highlighting any design inconsistency. As such the following action is recommended.</p> <ol style="list-style-type: none"> 1. The BIM model with LOD 400 to be used across the key workflows in the PC supply chain. <p>Chapter 5 discusses the deployment of constructible BIM alongside the purpose-built BIM cloud-enabled system called Production Logistic Management System (PLMS).</p>
2	Top management commitment	B1	The persistent commitment of top management on BIM adoption	<p>Management commitment in technology adoption may be summarised into belief and participation:</p> <ol style="list-style-type: none"> 1. Top management belief - positive beliefs of top managers about the usefulness of IT result managerial actions intended for diffusion of IT (Liang et al., 2007). The company's behaviour is guided by top managers' belief and mental image of desired future-state of operations (Srivastava, 1983). 2. Top management participation - the behaviour and actions performed to facilitate technology diffusion is essential (Ahire and Ravichandran, 2001). This encourage employees to adapt a new IT and workflows toward specific goals (Ba et al. 2001). They can take incremental steps and adjust the necessary levers to motivate, educate and obtain buy-in from employees (Henderson & Ruikar, 2010; Shen et al., 2016). This ultimately brings companies to higher levels of productivity (Srivastava, 1983). 	<p>Top management can take the following actions to ensure commitment to technology adoption, leading to productivity improvement.</p> <ol style="list-style-type: none"> 1. Belief: Provide visions and guidelines to the department managers about the opportunities in technology adoption. Publicly championing the future-state workflows to lend legitimacy to assimilating IT adoption. 2. Participation: Encourage department management and staff to commit time and provide all necessary information and resources for the success of this study. Appendix D illustrates the involvement of the management across the respective departments

3	Team coordination	D1	In a typical project, the precast design intent is discussed at the initial design stage, including design of precast structures and precast connections.	<p>Team coordination may be summarised as follow:</p> <ol style="list-style-type: none"> 1. Adjustment of one or more of the team members makes so that the goal is reached. And part of the coordination is about monitoring and feedback (Brannick 1997). 2. Team coordination can be managed by explicit or implicit mechanism and processes. Explicit: by programme (e.g. use workflows, procedures, scheduling) or by communication (e.g. formal submittals). Implicit: based on shared knowledge among team members (Espinosa & Fiore, 2004). 3. Construction knowledge and workflows can be utilised and improved if systematically captured and documented (Wang & Leite, 2012). However, most construction knowledge is tacit and resides in the minds of domain experts and the lack of organized processes to capture lessons learned for future reference. (Khalfan et al., 2002). 4. Previous research has conducted expert interviews to record their knowledge, or a particular workflow and asking practitioners to verbalise problems (Awad & Ghaziri, 2007; Ericsson & Simon, 1984; Lindlof & Taylor, 2010). 5. According to Zhang et al. (2017), BIM helps establish a communication platform for work teams, improved the quality of coordination. Implemented together with lean practices, it can also develop value adding workflow through work team coordination. 	<p>To improve team coordination, this research attempt to capture and document both explicit (e.g. workflow, tasks and schedules) and implicit (e.g. current practices) information so that the knowledge may be disseminated to other projects. As such, the follow actions are recommended.</p> <ol style="list-style-type: none"> 1. Capture and document all essential explicit information such as current tasks, task duration and roles of the key workflows in the PC supply chain. 2. Conduct interviews to capture information such as department practices and issues from subject-matter-experts (working in the respective departments) that impede team coordination. 3. Develop and apply the purpose-built IT system to improve team coordination. Chapter 5 presents the PLMS system that comprises three key modules.
4	Information sharing	D2	BIM models provided by structural engineers contain sufficient and accurate information, i.e., for further processing	<p>Information sharing may be summarised as follow:</p> <ol style="list-style-type: none"> 1. According to Koçoglu et al (2011), information sharing improves supply chain integration. It is a mechanism for feedback flow, strengthens the business relationships, allows more communication channel and transactions, as well as improve synergy and collaboration. 2. To encourage and improve inter-organizational coordination and information sharing, IT infrastructure and systems will become the enabler for real-time diffusion of information. (Bosch et al., 2015; Koçoglu et al, 2011; Liu et al., 2017; Nath & Standing, 2010). 	<ol style="list-style-type: none"> 1. To facilitate information sharing, purpose-built BIM cloud-enabled system was developed to improve communication, synergy and collaboration in projects. <p>Chapter 5 discusses the development of the BIM cloud-enabled system called Production Logistic Management System (PLMS).</p>

3.4.3 Determination of case studies within the PC supply chain

Methodologically, this part of the research was approached by means of case studies on a PC supply chain and the author has pursued the following steps, as illustrated in Figure 3-7. As discussed in the earlier section, the author will identify and examine key workflows to apply the PC-CSF performance factors for productivity improvement. For this part of the study.

Figure 3-7 Research workflow to determine case studies

Step 1: Seek research cooperation with a PC manufacturer

The selected PC manufacturer is one of the top PC manufacturers in Singapore, with annual sales revenue of more than \$30 million dollars in 2017. The selection was based on three key criteria: (1) the willingness and support of its management to provide the leadership and necessary resources to make changes. (2) A company that has already attained certain level of machinery automation, i.e., they are well configured for just-in-time (JIT) production system. The JIT system has been systematically studied in the manufacturing industry and has tremendous potential for PC production to minimise the delivery delays (Pheng & Chuan, 2001; Wang & Hu, 2017). It eliminates waste and enhance productivity, mainly by streamlining PC panel fabrication processes and inventory. Therefore, this study can further enhance the present supply chain workflow by focusing on their pre- and post-production phases. (3) A capable team that has fundamental BIM knowledge and experience. Table 3-7 summarises the profile of the selected PC manufacturer. However, the identity of the company is kept confidential.

Table 3-7 Brief profile of the selected PC manufacturer

No.	Years of experience in PC industry	More than 25
1	Number of employees	>250
2	Country of operation	Singapore, Malaysia, Thailand
3	Primary business	Residential (public & private), Non-residential
4	Track record (past 3 years)	S\$30m
5	Tendering limit (Singapore dollars)	Unlimited

In order to test the hypothesis, the strategies, methods and activities need to be carefully considered (Yin & Mckay, 2018). Firstly, the strategy adopted for this research was the co-validation strategy, whereby both the case study owner (i.e., the selected PC manufacturer) and the author work closely to apply the analytical model in real-world scenarios. According to Yin and Mckay (2018), such strategy capitalised on the wide experience and expertise of the case study owner to address pertinent issues. Secondly, to address real-world problem, the face validation method was chosen for this study (Yin & Mckay, 2018). Together with the case study owner, the author was able to conduct simulations and then analysed the simulated results. This method involved asking subject-matter-experts about the workflows and whether the simulated results were reasonable. Further modifications (if necessary) can be achieved until the case study owner was satisfied with the results.

Step 2: Top management support and commitment

To understand and refine the role and commitment of top management, the author elaborate on two stages in the process by which top management commit to an initiative such as technology adoption, namely belief and participation (see Table 3-6). (1) The alignment of beliefs gives direction to the company and has important implications for incentives and team coordination. According to Liang et al. (2007), it is a psychological state regarding to the potential and benefits of technology adoption and through such belief, top management can offer visions and guidelines to managers and the respective departments (Chatterjee et al., 2002). Besides, company's behaviour, such as publicly championing the future-state workflows, is guided by top managers' belief and mental image of desired future-state of operations (Srivastava, 1983). (2) According to Liang et al. (2007), higher level of top management participation will positively affect technology assimilation. In order to declare a success in IT adoption, top management participation will be required even after this

research has ended. Taking the co-validation strategy, the author and the top management of the company have agreed on the visions and guidelines for the company. To publicly champion the adoption of IT adoption, a kick-off meeting was conducted to share the visions, agree on the schedule and tasks ahead with the respective department managers and staff. In return, they were expected to commit time and provide the necessary resources to support this study.

Step 3: The interviews with key actors

The author met with the key actors from all the essential departments of the PC manufacturer (i.e., design department, the production department as well as the delivery and planning departments) to discuss and explain the research objectives. To contribute to a body of knowledge based on the life experiences of the interviewees, face validation method was chosen and semi-structured interviews were conducted. This method allowed the author to prepare questions ahead of time so that interviewers could discuss relevant topics within the limited timeline and opportunity the team had with the participants. Besides, it also allowed participants to freely express their views and experiences pertaining to the research topic. Appendix D provides the meetings schedule with the key actors.

Figure 3-8 Additional steps for clarification

The interviews were conducted over a period of more than one year. On average, the meetings took between three to several hours to complete. Depending on the complexity of the topics, multiple meetings were required to ensure the author could delve more deeply

into different aspects of the research issue. In most cases, interviews were recorded for documentation and later analysed. Figure 3-8 illustrates additional steps taken to ensure clarity and depth were achieved.

Essentially, the people who performed the works (e.g., production staff, logistic worker, draftsman and design engineers) could answer questions and clarify any misconception or contradicting statements on how tasks were performed and the challenges faced. One effective approach taken was to "walk the workflow" with the relevant employees.

Step 4: Collection of the current key workflows' information.

Two major categories of data were collected during the study, (a) procedural (workflow) data and (b) time data. Procedural (or workflow) data refer to the tasks, processes, current issues and the parties responsible for each task. Time data included the duration of each task, as well as the workers needed to perform that task. The combination of data obtained from the respective sources and angles of observation allowed the author to draw a more comprehensive picture of the key workflows in the PC supply chain.

a. Procedural (workflow) data

According to Alhalalat (2012), the term "workflow" comprises four main components. These are as follows: (1) "Task" is defined as core process of the workflow. (2) "Process" is defined as a set of activities design to produce a particular output. (3) "Information" refers to important content with regard to the task (e.g., data or facts), and (4) "Document" is how information is collected and stored, i.e., paper-based or electronic documents. Taking the deductive approach, the author then mapped the data collected to those specific categories.

The information was obtained and compiled after several interviews with the respective subject-matter experts that spanned across the various departments. The following information about the key workflows were identified. Table 3-8 summarises current workflow for the approval of shop drawing. The information was obtained from the design engineer and draftsmen.

Table 3-8 Current workflow for approval of shop drawing

No.	Task	Process	Information	Document	Practices and issues
1	Study of drawings	<ul style="list-style-type: none"> • Study of construction drawings • Clarification via RFI • Propose/Confirm panel naming 	<ul style="list-style-type: none"> • Work schedule • Submissions protocol • M&E provisions • Drawing numbering system 	Paper-based	No
2	Preparation of shop drawings	<ul style="list-style-type: none"> • Build BIM model • Prepare typical detail drawing • Produce panel shop drawings 	<ul style="list-style-type: none"> • BIM model • Shop drawings 	<ul style="list-style-type: none"> • Electronic • Paper-based 	No
3	Check by Engineer	Shop drawings checked by design engineer	Finalised shop drawings	Paper-based	No
4	Manual creation of master drawing list (MDL)	<ul style="list-style-type: none"> • Submission of drawings for approval. • Create master drawing list manually 	Master drawing list	Spreadsheet	<ul style="list-style-type: none"> • Manual creating of drawing & panel list in spreadsheet. • Tasks done manually; prone to data entry errors.
5	Shop drawings sent to MC ¹	Send to main contractor for approval	Transmittals	Emails with attached	Approval status not automatically tracked.
6	Manual monitoring of MDL	<ul style="list-style-type: none"> • Amendment • Resubmission • Monitor drawing status manually 	Shop drawing approval status	Spreadsheet	Track the drawings revisions manually.
7	Manual update of MDL	<ul style="list-style-type: none"> • Update planning co-ordinator of the changes • Put approved drawings • Put signed off drawings in approved folder 	Approved shop drawings for production	Spreadsheet and paper-based	<ul style="list-style-type: none"> • Drawing revisions saved in their personal computer. • Production and planning departments can't access the latest approved shop drawings, leading to the use of outdated drawings.

¹Main contractor (MC) – As per typical contractual agreement, all submittals are done through the main contractor.

Table 3-9 summarises the inventory management tasks, which is a combination of two distinct workflows, i.e., tracking and delivery. Both the production supervisor and the logistic staff have actively contributed to the data collection.

Table 3-9 Current workflow for inventory tracking and delivery

	No.	Task	Process	Information	Document	Practices and issues
Tracking of inventory	1	Assign storage location	<ul style="list-style-type: none"> • Final inspection • Locate storage at factory or temporary occupation licence² (TOL) area 	PC panel manufactured	Paper-based	No tracking system on PC panel.
	2	Move panel to location	<ul style="list-style-type: none"> • Loading of PC panel • Transfer of PC panel to location 	Location of PC panel at storage	Spreadsheet	No tracking system on PC panel.
	3	Update panel status	<ul style="list-style-type: none"> • Logistic to update location of PC panel 	Where about of PC panel	Spreadsheet	Manual update of PC panel storage location.
Delivery of inventory	4	Receipt delivery request	<ul style="list-style-type: none"> • Initiate delivery • Request received by logistic 	Delivery schedule	Paper-based	No
	5	Search panel	<ul style="list-style-type: none"> • Locate PC panel • Update of PC panel location • Ready for loading 	PC panel location identified	Paper-based	Lack of automated system to track and locate PC panel.
	6	Load panel for delivery	<ul style="list-style-type: none"> • Check for correct PC panel to be delivered according to schedule • Check for damages • PC panel loaded 	PC panel set for delivery	Paper-based	No tracking system on PC panel.
	7	Generate D/O	<ul style="list-style-type: none"> • Manual generation of Delivery Order (D/O) 	D/O for delivery	Paper-based	Errors in writing D/O manually.
	8	Transport to site	<ul style="list-style-type: none"> • Initiate internal/ contacted transportation • Hand over of PC panel to transporter • The transporter has to the D/O 	PC panel in-transit	Paper-based	Lack of monitoring system to status track delivery.
	9	Unload and sign-off	<ul style="list-style-type: none"> • Arrival • Check for correct PC panel delivered as scheduled • Check for damages • PC panel unload 	PC panel delivered	Paper-based	Errors in recording delivery report.

	10	D/O returns	<ul style="list-style-type: none"> • Transporter return the D/O • Filing of D/O 	PC panel delivery record	Paper-based	D/O may misplace due to the mishandling of paperwork.
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² Temporary occupation licence (TOL) - nearby land from the authorities on a basis for temporary additional storage.

Table 3-10 provides a summary of the current workflow of the progress claim and payment. The information was collected from the planning co-ordinator and logistic staff. In addition, issues in some of the tasks as encountered by the interviewees are presented. It is worth noting that the top management of the PC manufacturer has played a pivotal role to ensure the author was given the necessary help and cooperation.

In above table, master drawing list (MDL) is a list that tracks the revision of each shop drawing submitted for review. It comprises: (1) the production submission date, (2) the approved date, and (3) the reason for the delay associated with both the submission and decision. Panel list provides: (1) the number of panels at each level, unit and block of the project, (2) the number of shop drawings that are needed, (3) a list of different types of components, and (4) the manpower planning prior to the production. A transmittal is a brief letter, typically with a document attached to explain the contents. The content in a transmittal can be: (1) reference number, (2) date of the sending, (3) name details of sender and recipient, (4) project name, number, and other references to the project, (5) list of files sent (including file name, revision number and other relevant information), and (6) reason for the transmittal. Transmittals are often used in construction companies as a necessary communication tool in projects where a large number of documents are involved. From the PC manufacturer's point of view, they are a formal means of sending shop drawings, models, and others to another project member or to external project participant such as the main contractor.

Table 3-10 Current workflow for progress claim and payment

No.	Task	Process	Information	Document	Practices and issues
1	Create panel list	Creation of panel list	Scope of work	Spreadsheet	Manual creation of panel list
2	Update of casting record and delivery status	<ul style="list-style-type: none"> • Casting record • Delivery schedule 	<ul style="list-style-type: none"> • Delivery schedule • general erection sequence 	Spreadsheet	Casting record of production and planning department not in sync. Each update record separately.

3	D/O returns	<ul style="list-style-type: none"> • Transporter return the D/O • Filing of D/O 	PC panel delivery record	Paper-based	D/O may be misplaced due to the mishandling of paperwork, impacting payment.
4	Update claim progress	<ul style="list-style-type: none"> • Access and update claim status • Reconcile casting status and D/O 	PC panel to invoice	Spreadsheet	All the updates are done manually.
5	Prepare monthly claim	<ul style="list-style-type: none"> • Generate claim form • Approval from department manager • Approval from main contractor 	Approval for claim	Paper-based	<ul style="list-style-type: none"> • Manual process • D/O may not be located due to misplace.
6	Prepare invoice	<ul style="list-style-type: none"> • Check if approval given by main contractor • Generate invoice with supporting document 	Amount to be invoiced as approved	Paper-based	Manual check of approval.
7	Monitor payment	<ul style="list-style-type: none"> • Reconcile the amount receive versus claim 	Payment confirmation	Paper-based	Monitoring of payment is done manually.

b. Time data

The collection of present tasks and the respective timings were done across multiple interviews with the people who performed the respective tasks on daily basis. They had ample amount of experience and in-depth knowledge of the workflows. Therefore, it was possible to obtain the specific tasks in the pre- and post-production key workflows as well as the processing and waiting time of each task.

The data were obtained over the period of 12 months, across 22 projects and the unit used is man-day per project. Certain tasks required more than one person to accomplish the task. As such, an aggregation was taken to ensure measurement reflect real-world situations. The data collected were based on the “averaged time duration” observed from the previous precast projects for the present workflows. Due to the diversity and the complexity of the projects and panels involved, the time taken in each task could differ greatly. For instance, the size of the project may involve few hundreds of PC panels (for single residential building) to thousands of PC panels (for large public housing development). Proportionally,

the duration of each task within the three key workflows will increase. Therefore, the minimum and maximum of the processing time and wait time of each task were taken and the average timing was used for the tasks.

Table 3-11 shows the present timing of shop drawing approval tasks, Table 3-12 shows the present timing of both the tracking and the delivery of inventory tasks and Table 3-13 shows the present timing of progress claim and payment tasks. The manpower requirement is also indicated in each table. The data obtained from the PC manufacturer is confidential which cannot be presented in this thesis. Harmonic mean was used to compute the average timing because it is ideal for calculating the average of the ratios or rates (such as productivity), and also gave an equal weight to each data point (Balk, 2016). The harmonic mean of n numbers $x_1, x_2, \dots, x_n$ is calculated.

$$\bar{x}_H = \frac{n}{\frac{1}{x_1} + \frac{1}{x_2} + \dots + \frac{1}{x_3} + \frac{1}{x_4}} = \frac{n}{\sum_{i=1}^n \frac{1}{x_i}}$$

The harmonic formula for two data points:

$$\bar{x}_H = \frac{2}{\frac{1}{x_1} + \frac{1}{x_2}}$$

Table 3-11 Duration of tasks for shop drawing approval

No.	Task description	Worker needed	Processing time (man-day/project)			Wait time (man-day/project)		
			min	max	avg	min	max	avg
1	Study of drawings	5	5.0	15.0	7.5	13.0	17.0	14.7
2	Preparation of shop drawings	3	3.0	7.0	4.2	8.0	12.0	9.6
3	Check by Engineer	1	0.5	1.5	0.8	3.0	7.0	4.2
4	Manual creation of MDL	1	3.0	3.0	3.0	4.5	5.5	5.0
5	Shop drawings send to MC	1	1.5	3.0	2.0	2.0	6.0	3.0
6	Manual monitoring of MDL	1	1.5	3.0	2.0	3.0	6.0	4.0
7	Manual update of MDL	1	2.0	3.5	2.5	3.5	9.0	5.0
	Total	13			22.0			45.5

Table 3-12 Duration of tasks for tracking and delivery of inventory

No.	Task description	Worker needed	Processing time (man-day/project)			Wait time (man-day/project)		
			min	max	avg	min	max	avg
1	Assign storage location	1	0.5	0.5	0.5	3.0	7.0	4.2
2	Move panel to location	1	0.5	0.5	0.5	3.0	7.0	4.2
3	Update panel status	1	1.0	1.0	1.0	5.0	5.0	5.0
4	Receipt delivery request	1	1.0	3.0	1.5	3.0	5.0	3.8
5	Search panel	2	1.5	3.0	2.0	3.0	5.0	3.8

6	Load panel for delivery	2	3.0	5.0	3.8	7.0	13.0	9.1
7	Generate D/O	1	4.0	6.5	5.0	11.0	16.0	13.0
8	Transport to site	1	4.0	6.0	4.8	12.0	18.0	14.4
9	Unload and sign-off	2	1.0	1.0	1.0	3.0	7.0	4.2
10	D/O returns	2	1.5	3.0	2.0	8.0	13.5	10.0
	Total	14			22.0			71.7

Table 3-13 Duration of tasks for progress claim and payment

No.	Task description	Worker needed	Processing time (man-day/project)			Wait time (man-day/project)		
			min	max	avg	min	max	avg
1	Create panel list	1	6.5	10.5	8.0	13.0	17.0	14.7
2	Update of casting record and delivery status	1	2.5	6.0	3.5	3.0	9.0	4.5
3	D/O returns	1	0.5	1.0	0.7	4.0	6.5	5.0
4	Update claim progress	1	2.0	6.0	3.0	4.0	10.0	5.7
5	Prepare monthly claim	1	2.0	6.0	3.0	3.0	7.0	4.2
6	Prepare invoice	1	1.0	3.0	1.5	2.0	6.0	3.0
7	Monitor payment	1	1.0	3.0	1.5	8.0	13.5	10.0
	Total	7			21.2			47.1

3.4.4 Purpose-built BIM cloud-enabled system to support the PC-CSF performance factors

The primary purpose of the BIM cloud-enabled systems are to support the application of the PC-CSF performance factors. As presented in Table 3-6, BIM cloud-enabled system enable real-time diffusion of information and improve inter-organisational coordination and information sharing. When implemented together with lean practices, well-coordinated workflows can be expected. Chapter 5 describes the development of the BIM cloud-enabled system called Production Logistic Management System (PLMS). It comprises three key modules, each serving specific needs of the identified workflows. Namely, (1) System for Shop Drawing Approval, (2) System for Inventory Tracking and Delivery and proof of delivery, (3) System for Progress Claim and Payment. Every module can function as a standalone solution to support the identified workflows or combined to improve the overall productivity of the PC supply chain.

3.4.5 Apply the PC-CSF performance factors to the identified workflows

To apply the PC-CSF performance factors and determine the productivity gain of the newly developed workflows, the following steps were taken:

1. The current-state workflows were identified and analysed by means of VSM/A in chapter 4. As discussed in section 3.4.3, since the precast projects could vary in complexity and size, the minimum and maximum of the processing time and wait time were given by the PC manufacturer. An average was taken to reflect the typical PC project's processing time and wait time.
2. For each of the identified workflow, the PC-CSF performance factors were applied collectively, supported by the BIM cloud-enabled system called PLMS. The functionalities of each module within the PLMS were demonstrated to the experts from the different departments and everyone was asked to evaluate the system against the three key workflows. They have ample amount of experience and in-depth knowledge of the respective workflows, therefore it was possible for them to validate the outcomes of the newly developed workflows.

Chapter 6 discusses the implementation of PC-CSF performance factors according to the three identified workflows, namely (1) approval of shop drawing for production, (2) tracking and delivery of inventory and (3) progress claim and payment.

3.4.6 Collection of data

The collection of data was done across different groups of people who performed the respective tasks on daily basis. The newly developed workflows were estimated based on the expectation of the subject-matter experts from the PC manufacturer.

1. It was agreed that three likely outcomes could be expected from the deployment of the BIM cloud-enabled system. (1) Task eliminated. In this case, the specific task was removed from the current workflow due to automation provided by the PLMS system. (2) Task optimised. The specific task was improved, however human intervention was still required due to the nature of the task. Under such

circumstances, the experts were asked to estimate the percentage of improvement. And (3) not applicable or N.A., typically these were tasks that involve physical and manual works, as such transportation of the PC panel.

2. As productivity is a measure of progress, it is essential to have a reference state. For the purpose of this research, the productivity gained was based on the comparison between the “average values” for the current workflow and “expected values” for the newly developed workflow which is discussed in chapter 6.

The combined PC-CSF performance factors were applied to each of the identified key workflow. The results discussed in chapter 6 will determine if the hypothesis H_9 should be accepted or rejected.

3.5 Summary

The study involved both qualitative and quantitative methods to address the five research objectives set out in chapter 1. Firstly, the conceptual BIM adoption model for PC manufacturers was presented. By placing the emphasis on CSFs, PC manufacturers can navigate towards higher levels of BIM utilisation. As such, the PCBIM hexagon framework was proposed and the questionnaires were derived from the framework to generate the CSFs for BIM adoption among PC manufacturers. Secondly, to further understand how these CSFs may directly contribute to productivity improvement to the PC manufacturers, hypotheses were formulated and multiple regression was conducted to assess and shortlist the factors. The author called these factors the “PC-CSF performance factors”. Thirdly, to demonstrate the usefulness of the PC-CSF performance factors on the PC manufacturer and its supply chain, a hypothesis was set and key workflows were identified as case studies. To improve the productivity of each workflows, the combined benefits of the PC-CSF performance factors should be applied (supported by the purpose-built BIM cloud-enabled systems). Primary data were then obtained by working closely with the subject-matter-experts from the selected PC manufacturer. Finally, productivity improvement brought about by the combined benefits of the PC-CSF performance factors was analysed and presented.

Chapter 4 : The analysis of data

This chapter describes the approach to establish the CSFs for BIM adoption among PC manufacturers. From the questionnaire survey, a total of eight CSFs were established. As a novel contribution, we investigate to what extent these CSFs may contribute to productivity improvement. By means of regression analysis, a total of four factors were shortlisted and the “PC-CSF performance analytical model” was developed.

To demonstrate the usefulness of the combined PC-CSF performance factors in real-world scenarios, a hypothesis was formulated and three key workflows in the PC supply chain were identified as case studies. Using value stream mapping technique, the current tasks, duration, roles and responsibilities were analysed.

4.1 Establish the key factors for BIM adoption in PC manufacturers

The survey invitations were sent out to 77 PC manufacturers, and 53 were returned with valid responses, accounting for a response rate of 69%. In most cases, the respondents graded the survey questions as “neutral”, “important” or “very important”. But there were few respondents who also graded “not important” to some of the questions occasionally. The raw survey data are presented in appendix B.

Table 4-1 Company profile of the respondents

No.		Companies' profile	Number	Frequency	Percentage (%)
1	Years of experience in PC industry	<5	4		7.5%
		5 to 10	7		13.2%
		11 to 20	16		30.2%
		21 to 30	9		17.0%
		31 to 40	10		18.9%
		>40	7		13.2%
2	Number of employees	<50	16		30.9%
		51 to 250	21		39.6%
		>250	16		30.2%
3	Country of operation	Singapore		47	88.7%
		Malaysia		32	60.4%
		Other countries (many ASEAN countries and some European countries)		36	67.9%
4	Primary business	Residential (public & private)		42	79.2%
		Non-residential		39	73.6%
		Infrastructure		15	28.3%

Table 4-1 presents the company profiles. The majority of the surveyed companies have more than 10 years of experience in the PC industry. Assuming companies having less than 50 employees are small (S) size, between 51 and 250 employees are medium (M) size, and above 250 employees are large (L) size, then the numbers of the small, medium and large companies are close. Most of the companies have multinational locations operating in various countries including most ASEAN countries, China, Korea, Taiwan, the Middle East, and Finland. Their businesses are mainly in residential, industrial and commercial buildings with a few in civil infrastructure. Hence, the samples are considered representative of the present PC industry.

The surveyed PC manufacturers were placed onto the developed BIM adoption model as shown in Figure 4-1. Strictly speaking, till present, none of the surveyed PC manufacturers can be qualified as BIM level 3 – iBIM, in which BIM use will be extended into the operation of assets over their lifetimes. Allocation of the companies in the grid chart in terms of BIM maturity level is based on the following four areas: (1) content, (2) digitalisation, (3) interoperability, and (4) collaboration, which are proposed by Poljanšek (2017) in his report on BIM standardisation.

Figure 4-1 Status of 53 PC manufacturers in BIM adoption model

According to the selected items the respondents gave, the BIM maturity levels were determined. However, it was difficult to generate the BIM adopters' model since the respondents all expressed their keen interest in new technologies. In this regard, some rules were applied. The first rule was to look at their years of experience. If the company has been in the industry for a long time but its BIM maturity level was still low, there are reasons to believe the company is conservative towards new technology. Thus, they are in the group of late majority or laggards. The second rule was to look at their records of

involving innovations. For example, in Singapore, some PC manufacturers are in the Integrated Construction and Prefabrication Hub (ICPH). These companies are believed to be technology pioneers. As such, the author stratified the companies in terms of BIM adopters' model. Refer to appendix C for more details.

According to the yearly National BIM report (2019), the use of BIM in small companies are generally low. However, medium and large companies have adopted BIM. It can be seen from Figure 4-1 that although the late majority and laggards are mostly small companies, they can also become “technology risk-takers”. This corresponds with the finding reported by Ayinla and Adamu (2017) that the size of a company does not necessarily make it an innovator. Similarly, larger companies can be “change-resistant” too.

4.1.1 Data reliability

Cronbach's alpha (often symbolised by the lower case Greek letter α) is the most widely used index of the reliability of a summated rating scale (Cronbach, 1951). A scale is formed by multiple Likert questions in a survey. The general formula for calculating α is:

$$\alpha = \frac{N}{N - 1} \left(1 - \frac{\sum_{i=1}^N \alpha_{Y_i}^2}{\alpha_X^2} \right)$$

Where $X = Y_1 + Y_2 + \dots + Y_N$, N is the number of survey items in the scale, α_X^2 is the variance of the observed total scores, and $\alpha_{Y_i}^2$ is the variance of item i for the current sample of persons. Typically, α ranges from 0 to 1. Nunnally (1978) offered a rule of thumb that a value of 0.70 or better is acceptable. It is true that the higher the correlations among the items in the scale, the higher the value of α will be, but vice versa is not always true because α is also strongly affected by the number of items (Streiner, 2003). In fact, α will increase when the number of items of a scale keeps increasing even though the average correlation remains unchanged.

In order to produce a sufficiently precise estimate of the population α , the sample size P should not be too small. Statisticians have debated on the minimum sample size to compute α . The most widely used rule of thumb checks the ratio of the sample size P to the number

of survey items N , which varies from 3 to 10 according to different authors (Cattell , 1978; Everitt, 1975; Gorsuch, 1983; Nunnally, 1978).

Table 4-2 presents the calculated α for every subscale of the current survey. They are all above the experimental threshold of acceptance which is 0.7. The survey can thus be treated as reliable.

Table 4-2 Cronbach's alpha for every subscale of the survey

	Areas	Sample size, P	Survey items, N	Cronbach's alpha, α
A	The government and the eco-system	53	5	0.71
B	The company	53	5	0.89
C	The team	53	5	0.73
D	The process	53	5	0.84
E	The BIM software tool	53	5	0.72

4.1.2 The evolutionary approach for ranking

In this study, the author translated the critical success factor identification problem into the document ranking problem and tries to use the list-wise based rank learning model to find the most important factors contributing to BIM adoption in PC manufacturers. The problem is modelled in this way: there are m respondents and n factors. let $l^j = \{l_1^j, \dots, l_n^j\}$ be the relevance labels associated with the factors in the list given by respondent j . l_i^j is the judgment score provided by the respondent j regarding factor i . And let $r^j = (r_1^j, \dots, r_n^j)$ be the ranking of the factors in the list in light of l^j . The rank r_i^j of factor i is an integer in $\{1, \dots, n\}$, where 1 is the first position and n is the last one.

The objective of the learning in this study was to find the best ranking $\pi = (\pi_1, \dots, \pi_n)$. To this end, the author aimed to develop an evolutionary strategy which is a genetic algorithm in nature to effectively and efficiently converge towards a better solution. A solution (chromosome) is a vector of genes $\theta = (\theta_1, \dots, \theta_n)$, where each gene θ_i is a real number representing the judgment score. And $\vartheta = (\vartheta_1, \dots, \vartheta_n)$ is the corresponding ranking. Each solution was then evaluated by the total variances of rankings of every respondent judgment scores from it which is calculated using the following formula:

$$v = \sum_{j=1}^m v^j = \sum_{j=1}^m \sum_{i=1}^n (r_i^j - \vartheta_i)^2$$

The optimisation objective was to find the solution having the minimum v . The initial population was generated from both the training data and the random data. The algorithm is with the following features: tournament selection, single-point crossover, and uniform mutation. The procedure of the proposed learning algorithm is described below:

Learning Algorithm: Rank GP-ES ($\mu + \lambda$)
Input: Survey data
Output: An optimal ranking function
1. Initialisation (1) Generate the initial population of size φ (2) Calculate the fitness for every individual (3) Select μ best individuals 2. While the maximum iteration ξ is not reached, do (1) Using the tournament selection method to select parents (2) Apply genetic operators (crossover, mutation) to generate λ children (3) Calculate the fitness for every new individual (4) Select best μ parents between $(\mu + \lambda)$ End 3. Output the best ranking function

The overall quality of a respondent's data can be measured using a popular metric, namely the discounted cumulative gain (DCG), which is defined as below:

$$DCG^j = \sum_{i=1}^n \frac{2^{l_i^j} - 1}{\log_2 \pi_i + 1}$$

DCG is non-negative and the higher value the better.

4.1.3 Identification of CSFs for BIM adoption

According to Fernandez-Preto et al. (2012), there are no specific rules for choosing appropriate values as parameters. Many researchers have based on their choices to tune the control parameters, experimenting with different values and selecting the optimal setting that give the best results. However, the solution quality and computational time are positively correlated. In this regard, a compromise is necessary to generate an acceptable solution in a relatively reasonable computational time, i.e., a large population size will typically impose a large cost per generation, as such trial and error approach is required (Schaffer et al. 1989). For this research, multiple independent runs were conducted. The parameters associated with the evolutionary learning algorithm were chosen as shown in Table 4-3.

Table 4-3 Parameter setting for the learning algorithm

Parameters	Values
Population size φ	300
Number of elitists μ	100
Number of children λ	100
Crossover probability P_c	0.9
Mutation probability P_m	0.4
Maximum iteration ξ	100
Multiple run γ	20

The rank results are presented in Table 4-4. The lower value represents higher importance.

Table 4-4 Ranking of factors

Factors	Rank						
	All	Level ¹ 0	Level 1	Level 1	Level 2	Level 2	Level 2
		Group ² 0	Group 0	Group 1	Group 0	Group 1	Group 2
A1	1	1	1	2	2	2	1
A2	2	2	2	2	2	2	2
A3	2	1	2	2	2	2	2
A4	2	2	1	2	1	2	1
A5	1	1	1	1	1	2	1
B1	1	1	1	1	1	1	1
B2	2	2	2	1	2	2	2

B3	2	1	2	2	3	2	1
B4	2	2	2	2	2	2	2
B5	2	1	2	1	1	1	1
C1	2	1	2	2	1	2	2
C2	2	2	2	2	2	1	1
C3	2	1	2	2	2	2	2
C4	2	1	2	2	3	2	2
C5	2	2	2	2	3	2	2
D1	1	1	1	2	2	1	1
D2	1	1	1	2	1	1	1
D3	1	1	1	2	2	1	1
D4	2	1	2	2	3	1	2
D5	1	1	1	2	2	1	1
E1	2	1	2	2	1	2	1
E2	2	1	2	3	3	2	3
E3	2	2	2	3	2	1	2
E4	2	2	2	2	2	2	2
E5	1	2	1	2	1	1	1
Sum of rank 1	8	16	9	4	8	10	13

₁ Level – BIM maturity level

₂ Group – BIM adopters' group

There were totally eight factors as the most important factors to BIM adoption, which are: (1) A1 – Government policies and support on BIM implementation in precast sector, (2) A5 – BIM to be used as a competitive advantage, (3) B1 – The persistent commitment of top management on BIM adoption, (4) D1 – In a typical project, the precast design intent is discussed at the initial design stage, including design of precast structures and precast connections. (5) D2 – BIM models provided by structural engineers contain sufficient and accurate information, i.e., for further processing. (6) D3 – Data extracted from the BIM models improve productivity. (7) D5 – Drawing production can be faster if changes are well-controlled and hence shorten production time, (8) E5 – The availability of local support team, i.e., BIM software vendors timely technical support.

It is interesting to see that both the industry pioneers and the laggards tend to give significantly more CSFs than the other companies. Perhaps for the industry pioneers, their rich experience in new technologies enables them to have a more clear and compressive view while for the laggards, their eagerness of new technologies to change their current backward situation urges them to recognise the importance of the factors.

Table 4-5 The discounted cumulative gain of every respondent

Index	Company size	Level ¹	Group ²	MDCG	Index	Company size	Level	Group	MDCG
1	S	0	0	560.31	28	L	1	1	476.17
2	S	0	0	223.65	29	L	1	1	317.93
3	S	0	0	498.88	30	M	2	0	360.03
4	S	0	0	389.93	31	S	2	1	328.03
5	M	0	0	426.93	32	M	2	1	530.03
6	S	1	0	360.94	33	M	2	1	448.79
7	S	1	0	239.65	34	M	2	1	265.74
8	S	1	0	362.12	35	M	2	1	375.17
9	S	1	0	454.22	36	M	2	1	322.98
10	S	1	0	511.07	37	M	2	1	414.31
11	S	1	0	463.55	38	L	2	1	344.89
12	M	1	0	454.31	39	L	2	1	242.60
13	M	1	0	317.93	40	L	2	1	481.22
14	M	1	0	285.93	41	S	2	2	550.22
15	M	1	0	431.60	42	M	2	2	443.36
16	L	1	0	301.93	43	M	2	2	481.22
17	L	1	0	358.74	44	M	2	2	580.50
18	L	1	0	288.89	45	M	2	2	385.27
19	L	1	0	480.81	46	M	2	2	308.70
20	S	1	1	445.84	47	M	2	2	570.41
21	S	1	1	260.70	48	L	2	2	537.60
22	S	1	1	317.93	49	L	2	2	494.69
23	S	1	1	270.79	50	L	2	2	406.74
24	M	1	1	361.29	51	L	2	2	473.65
25	M	1	1	385.27	52	L	2	2	314.55
26	L	1	1	462.69	53	L	2	2	126.25
27	L	1	1	308.89					

¹ Level – BIM maturity level

² Group – BIM adopters' group

Furthermore, Table 4-5 provides the DCG value of every respondent based on the ranking made by all the respondents. In general, there is a positive relationship between the average DCG value and the BIM adopter groups, i.e., the more willingness of a group to adopt new technologies, the higher the average DCG value that group will have. This suggests that companies which are actively involving in new technologies usually have more capabilities to identify the CSFs. Therefore, their opinions could be more weighted.

4.1.4 Identification of CSFs that contribute to productivity improvement

To test hypothesis H_1 to H_8 , multiple regression was conducted. By using the CSFs as predictor variables to predict the outcome of PC2 (i.e., the company uses BIM for productivity improvement) as dependent variable (refer to appendix B). With the utilisation of SPSS, the results of regressions on the single dependent variable PC2 and the independent variables are depicted in Table 4-6.

R-squared (R^2) is a goodness-of-fit measure for regression models. It evaluates the scatter of the data points along the fitted regression line and ranges from 0 to 1. The higher the R-squared value, the smaller the differences between the obtained data and the fitted values, the better the model fits the obtained data. However, the R-squared value always increases when additional independent variable is added to a model, even if the independent variable is insignificant. On the other hand, the adjusted R-squared value only increases when independent variable is significant or decreases if the independent variable does not help in predicting the dependent variable. As such, adjusted R-squared should be used while selecting important predictors (independent variables) for this regression model. Table 4-6 indicates that the adjusted R-squared value is 0.691, which implied a good-fit model. This signals that 69% of the time, the dependent variable can be explained by the eight CSFs. The F-tests in the regression analysis is significant at 95% confidence level (a p-value below 0.05), which also indicates that the overall model is statistically significant.

Multi-collinearity occurs when independent variables in a regression model are correlated. In such situation, the statistical power of the regression model is weakened, and the p-values to identify independent variables that are statistically significant may not be trusted. An effective test to assess multi-collinearity is to examine the variance inflation factors (VIF), which is an index that measures the high inter-correlations among the independent variables. The rule of thumb is that the value of VIF is 10 (or above) and the value of tolerance is less than 0.2, then the multi-collinearity would be problematic (Kutner et al., 2004). The largest value of VIF in Table 4-6 is merely 2.283, which indicates that multi-collinearity would not increase the standard errors of the model and that the model is dependable.

Table 4-6 Regression of productivity improvement – PC2

PC2	R	R-Squared	Adjusted R-squared
	0.860	0.739	0.691

ANOVA of PC2	Sum of Squares	df	Mean Square	F	Sig.
Regression	17.648	8	2.206	15.557	.000
Residual	6.239	44	0.142		
Total	23.887	52			

	Unstandardised Coefficients		Standardised Coefficients	t	Sig.	Collinearity Statistics	
Predictor variables	B	Std. Error	Beta			Tolerance	VIF
(Constant)	0.152	0.450		0.339	0.737		
A1	0.057	0.079	0.066	0.720	0.476	0.702	1.424
A5	0.048	0.124	0.045	0.389	0.699	0.438	2.283
B1	0.243	0.100	0.268	2.420	0.020	0.484	2.065
D1	0.162	0.065	0.238	2.486	0.017	0.647	1.546
D2	0.132	0.053	0.224	2.501	0.016	0.743	1.347
D3	0.266	0.084	0.330	3.179	0.003	0.551	1.815
D5	0.051	0.072	0.067	0.706	0.484	0.656	1.524
E5	0.048	0.101	0.055	0.478	0.635	0.446	2.244

The regression analysis has also indicated the following variables to be statistically significant and positively associated with PC2 (productivity improvement). The four variables are: top management commitment (B1), team coordination (D1), information sharing (D2) and constructible BIM (D3). The author called these factors the “PC-CSF performance factors”.

However, government policies (A1), competitive advantage (A5), drawing approval (D5) and local support (E5) had p-values greater than the significance level, which implied there was insufficient evidence in the sample to reject the null hypothesis. The results of the hypotheses testing from H_1 to H_8 are explained below.

H₁: There is no significant ($\alpha < 0.05$) impact of Government policies (A1) on the productivity improvement of the PC manufacturers ($p = 0.476 > 0.05$). It was hypothesised that Government policies positively impact the productivity of the PC manufacturers. This hypothesis was rejected ($\beta = 0.057$; $t = 0.720$).

H₂: This is no significant ($\alpha < 0.05$) effect of BIM competitive advantage (A5) on the productivity improvement of PC manufacturers ($p = 0.699 > 0.05$). It was

hypothesised that BIM competitive advantage improves the productivity of PC manufacturers. This hypothesis was rejected ($\beta = 0.048$; $t = 0.389$).

H₃: There is a direct significant ($\alpha < 0.05$) effect of top management commitment (B1) on the productivity improvement of PC manufacturers ($p = 0.02 < 0.05$). It was hypothesised that top management commitment improves the productivity of PC manufacturers. This hypothesis was supported ($\beta = 0.243$; $t = 2.420$).

H₄: There is a direct significant ($\alpha < 0.05$) effect of team coordination (D1) on the productivity improvement of PC manufacturers ($p = 0.017 < 0.05$). It was hypothesised that team coordination in the organisation improves the productivity of PC manufacturers. This hypothesis was supported ($\beta = 0.162$; $t = 2.486$).

H₅: There is a direct significant ($\alpha < 0.05$) effect of information sharing (D2) on the productivity improvement of PC manufacturers ($p = 0.016 < 0.05$). It was hypothesised that Information sharing across different departments improves the productivity of PC manufacturers. This hypothesis was supported ($\beta = 0.132$; $t = 2.501$).

H₆: There is a direct significant ($\alpha < 0.05$) effect of constructible BIM (D3) utilisation on the productivity improvement of PC manufacturers ($p = 0.003 < 0.05$). It was hypothesised that utilisation of constructible BIM improves the productivity of the PC manufacturers. This hypothesis was supported ($\beta = 0.266$; $t = 3.179$).

H₇: This is no significant ($\alpha < 0.05$) effect of faster drawing approval (D5) on productivity improvement of PC manufacturers ($p = 0.484 > 0.05$). It was hypothesised that faster drawing approval (D5) improving productivity of the PC manufacturers. This hypothesis was rejected ($\beta = 0.051$; $t = 0.706$).

H₈: There is no significant ($\alpha < 0.05$) effect of local support (E5) on the productivity improvement of the PC manufacturers ($p = 0.635 > 0.05$). It was hypothesised that the availability of local support from BIM software vendors improves productivity. This hypothesis was rejected ($\beta = 0.048$; $t = 0.478$).

The respective t-value is calculated by dividing the coefficient (β) with its standard error. A t-value of zero indicates that the sample results exactly equal the null hypothesis. As such, the greater the magnitude of t-value, the greater the evidence against the null hypothesis. Table 4-7 summarises the results of hypotheses testing, as indicated in the t-value.

Table 4-7 Results of the hypotheses testing

Parameters	Respective Hypothesis	Regression coefficient(β)	t-value	Significance at 0.0.5
A1 $\rightarrow$ PC2	H ₁ The Government policies (A1) positively impact the productivity of the PC manufacturers	0.057	0.720	Insignificant
A5 $\rightarrow$ PC2	H ₂ The BIM competitive advantage (A5) improves the productivity of PC manufacturers	0.048	0.389	Insignificant
B1 $\rightarrow$ PC2	H ₃ The top management commitment (B1) improves the productivity of PC manufacturers.	0.243	2.420*	Significant
D1 $\rightarrow$ PC2	H ₄ Team coordination (D1) in the organisation improves the productivity of PC manufacturers.	0.162	2.486*	Significant
D2 $\rightarrow$ PC2	H ₅ Information sharing (D2) across different departments improves the productivity of PC manufacturers.	0.016	2.501*	Significant
D3 $\rightarrow$ PC2	H ₆ The utilisation of constructible BIM (D3) improves the productivity of the PC manufacturers.	0.003	3.179**	Significant
D5 $\rightarrow$ PC2	H ₇ Faster drawing approval (D5) improving productivity of the PC manufacturers.	0.484	0.706	Insignificant
E5 $\rightarrow$ PC2	H ₈ The availability of local support (E5) from BIM software vendors improves productivity.	0.048	0.478	Insignificant

*p-value < 0.05

**p-value<0.01

Based on the above analysis, the estimated multiple regression model can be written, where $\epsilon = 0$. The author called it the “PC-CSF performance analytical model”.

$$\text{Productivity improvement (PC2)} = 0.152 + 0.243B1 + 0.162D1 + 0.132D2 + 0.266D3$$

Figure 4-2 illustrates the causal relationship between the dependent and independent variables.

Figure 4-2 The PC-CSF performance analytical model

Regression coefficients represent the mean change in the dependent variable for one unit of change in the predictor variable while holding other predictors in the model constant. In other words, the higher the coefficient, the larger the effect on the dependent variable. Table 4-8 presents the four PC-CSF performance factors, from the largest to the smallest coefficients.

Table 4-8 The four PC-CSF performance factors in the PC-CSF performance analytical model

No.	Construct	Code	Predictor variables	Regression coefficients	Statistical significant	VIF
1	Constructible BIM	D3	Data extracted from the BIM models improve productivity	0.266	0.003	1.815
2	Top management commitment	B1	The persistent commitment of top management on BIM adoption	0.243	0.020	2.065
3	Team coordination	D1	In a typical project, the precast design intent is discussed at the initial design stage, including	0.162	0.017	1.546

			design of precast structures and precast connections			
4	Information sharing	D2	BIM models provided by structural engineers contain sufficient and accurate information, i.e., for further processing	0.132	0.016	1.347

4.2 Identification of key workflows as case studies for the application of PC-CSF performance factors

As presented in section 3.4.3, a total of three workflows were deemed as essential by the subject-matter-experts and have been identified as case studies to test the hypothesis H₉. They are: Case 1, the approval of shop drawing for production, Case 2, the tracking and delivery of inventory and Case 3, the progress claim and payment. Incidentally, these are key workflows in the pre- and post-production phases.

Figure 4-3 presents the key workflows of the pre-production, production and post-production phases of the PC supply chain. They are closely interlinked in practice, therefore, any delay in one of the phases will impact the productivity of the entire supply chain. Since the selected company has already attained certain level of automation for just-in-time (JIT) production at the production phase. The application of the combined PC-CSF performance factors is expected to further enhance the productivity of the selected PC manufacturer (and its supply chain) when applied to the key workflows of the pre- and post-production phases.

Figure 4-3 Key workflows of PC supply chain

Visualising the three key workflows with value stream mapping and analysis (VSM/A) technique

Referring to section 3.4.3, two major categories of data were collected during interviews (1) procedural (workflow) data and (2) time data. The VSM/A technique which was briefly discussed in section 2.2.3, was selected to assist the author present the time data visually and help with introspection, i.e., analysis of the current workflow which leads to process improvement. This tool displays all key tasks in the workflow and quantifies the processing time and wait time for each task. For each key workflow, there are two kinds of value stream maps to be created, i.e., current-state (or original state) and future-state (newly developed workflow). The current-state value stream map is used to determine what the present workflow currently looks like and the future-state value stream map the process after the PC-CSF performance factors are applied to the workflow, also called the newly developed workflow. Chapter 6 presents the newly developed workflows and the attained productivity improvement.

Referring to Figure 4-4, each box represents a task in the workflow. The value-add time or processing time (measured in man-day per project) is indicated at the top of each box, and the wait or queue time (measured in man-day per project) shows how long the task must wait as indicated by the arrows between the triangles (the triangles represent start and end of a task). Finally, the straight thin line with arrowhead shows the flow of work from one task to the next.

Figure 4-4 VSM symbols

The current time data of the three key workflows were extracted from Table 3-11, Table 3-12 and Table 3-13 respectively. The following sections discuss each of the current-state key workflows.

4.2.1 Case 1 - Approval of shop drawing for production

Figure 4-5 presents the value stream mapping of the typical shop drawing approval workflow. The mapping includes the activities predominantly performed by selected PC manufacturer and main contractor. As per typical contractual agreement, all submittals are done through the main contractor. Each box represents a task of the overall workflow and the duration (processing time and wait time) of the tasks are obtained from Table 3-11.

Figure 4-5 VSM for approval of shop drawing – current workflow

Once the construction drawings are received from the main contractor, The PC manufacturer will study those drawings (Task 1) before generating shop drawings (Task 2). Otherwise, they will raise requests for information (RFIs) to the man contractor for clarification. The first set of shop drawings will typically exclude Mechanical, Electrical, and Plumbing (MEP) details. At this point, all shop drawings will be checked by the department Engineer (Task 3) before it is manually recorded and tracked in the master drawing list (MDL). However, the number of shop drawings will increase with the complexity of the construction project. For this reason, the MDL creation (Task 4) task is prone to data entry errors. Refer to appendix E for the explanation of MDL.

The shop drawings will then be forwarded to the man contractor, and subsequently to the consultant for review (Task 5). If an amendment is necessary, the process will continue until those drawings are approved. The final two tasks are MDL monitoring (Task 6) and the update of drawings status (Task 7). Currently, the individual who performs these tasks will have their own copy of the drawing revisions saved on their respective personal computer. It is only at a later stage (on weekly or monthly basis) that they will combine and update into the MDL. Such manual process has been proven to be tedious, time-consuming and prone to human errors. The manpower requirement, average current processing time and wait time for each activity are summarised in Table 4-9, the unit of measurement is in man-day per project.

Table 4-9 Present timing of approval of shop drawing

No.	Task description	Role/ staff involved	Present workflow		
			No. of worker	Processing time (man-day/ project)	Wait time (man-day/ project)
1	Study of drawings	Design engineer	1	7.5	14.7
		Draftsman	3		
		Planning co-ordinator	1		
2	Preparation of shop drawings	Draftsman	3	4.2	9.6
3	Check by engineer	Design engineer	1	0.8	4.2
4	Manual creation of MDL	Draftsman	1	3.0	5.0
5	Shop drawings send to MC	Draftsman	1	2.0	3.0
6	Manual monitoring of MDL	Draftsman	1	2.0	4.0
7	Manual update of MDL	Draftsman	1	2.5	5.0
Total			13	22.0	45.5

Referring to Table 4-10 on the value stream analysis results, the total number of man-days needed to complete a single project on average is 68 man-days. However, the total processing time is merely 22 man-days. In other words, only 33% of the total time is value-added time, and the rest of 67% is the non value-added time.

Table 4-10 Present workflow - wait time and processing time

	Duration of current workflow (man-day/project)	Percentage of total (%)
Total wait time	46	67%
Total processing time	22	33%
Total time for approval of drawings	68	100%

4.2.2 Case 2 - Tracking and delivery of inventory

Figure 4-6 presents the value stream mapping of the present inventory tracking and delivery process. The mapping predominantly includes the tasks performed by the PC manufacturer and the duration of the tasks were obtained from Table 3-12. In a typical PC production run, many unique panels are cast and shipped daily. The PC manufacturer needs to assign storage location (Task 1) and physically transport the panel to the location (Task 2). Due to space constraint, the common practice of the PC manufacturer is to rent a nearby piece of land from the authorities on a temporary occupation licence (TOL) basis for additional storage. However, this poses another problem as the number of PC panels increases. It becomes difficult to locate and in certain situation, panels need to be recast to meet the delivery schedule. In the current workflow, the location information is manually recorded on a spreadsheet for future access (Task 3). Once the request of delivery is received (Task 4), the search of the specific panel commences and is done manually (Task 5), i.e., the logistic worker needs to access the spreadsheet to locate the PC panel and then physically retrieve the panel. Since there is no system to track each PC panel, it is common for the PC manufacturer to invest substantial amount of resources and time to track and locate the PC panel. According to the PC manufacturer, the physical search for the specific panel may take as long as a day to locate which in turn possibly causes delivery delay.

Figure 4-6 VSM for inventory tracking & delivery – current workflow

The delivery process commences once the specific panel is loaded on the transporter (Task 6). Before the PC panel is shipped out of the PC manufacturer, the delivery order (D/O) needs to be generated (Task 7) and is manually created, i.e., paper-based documents. Thus, data entry errors as well as delivery orders misplacement can be expected. The transfer of panel to the construction site begins (Task 8) once all documentation is ready. Upon arrival, the receipt of the PC panel is done manually (Task 9), so is the return of D/O (Task 10). The lack of visibility into the delivery status has negative impact on the supply chain. The situation is exacerbated when the D/O is lost or damaged, impacting progress payment.

The current workflow for the monitoring and locating of inventory is cumbersome operationally and involves production and logistic staff together with the planning coordinator. The manpower requirement, average current processing time and wait time for each task are tabulated in Table 4-11.

Table 4-11 Present timing of tracking and delivery of inventory

No.	Task description	Role/ staff involved	Present workflow		
			No. of worker	Processing time (man-day/ project)	Wait time (man-day/ project)
1	Assign storage location	Production Staff	1	0.5	4.2
2	Move panel to location	Planning Co-ordinator	1	0.5	4.2
3	Update panel status	Logistic Staff	1	1.0	5.0
4	Receipt delivery request	Logistic worker	1	1.5	3.8
5	Search panel	Production Staff	1	2.0	3.8
		Logistic worker	1		
6	Load panel for delivery	Logistic worker	2	3.8	9.1
7	Generate D/O	Logistic worker	1	5.0	13.0
8	Transport to site	Logistic worker	1	4.8	14.4
9	Unload and sign-off	Planning Co-ordinator	1	1.0	4.2
		Logistic Staff	1		
10	D/O returns	Planning Co-ordinator	1	2.0	10.0
		Logistic Staff	1		
Total			14	22.0	71.7

It is worth noting that each delivery was done in batches of 5 to 10 PC panels, depending on the panel size. Furthermore, multiple projects can be undertaken at any one time in the PC factory. Therefore, the average time for the tracking and delivery processes are taken and the unit is in man-day per project.

Table 4-12 summarises the value stream analysis results, the number of days needed to complete a single project on average is 94 man-days. However, the total processing time is merely 22 man-days. In other words, only 23% of the total time is value-added time, and the rest of 77% is the non value-added time.

Table 4-12 Present workflow - wait time and processing time

	Duration of current workflow (man-day/project)	Percentage of total (%)
Total wait time	72	77%
Total processing time	22	23%
Total time for tracking and delivery of inventory	94	100%

4.2.3 Case 3 - Progress claim and payment

Figure 4-7 presents the value stream mapping of the present progress claim and payment workflow. The duration of the tasks are obtained from Table 3-13.

The planning department is responsible for the creation of the panel list (Task 1), delivery schedule and updates of casting and delivery record (Task 2) on a daily basis. Currently, the creation of panel list is done manually and thus, it is time-consuming and is error prone. It is further complicated by the fact that the list is usually kept in spreadsheets that reside with individuals. To initiate a progress claim of a specific PC panel, the planning coordinator must first reconcile the casting status (to verify that the panel is cast and ready to ship out) with the delivery status (the panel is physical delivered to the main contractor). The return of the delivery order (Task 3) indicates that the PC panel has been physically delivered on site and the planning coordinator may update the progress claim progress status accordingly (Task 4). However, due to a lack of automation, all the updates are done manually.

The next step is to prepare the monthly claim (Task 5). The claim amount is calculated based on the type rate (unit price) and the payment schedule (criteria) as approved by the main contractor. The PC manufacturer can only submit their invoices (Task 6) when the main contractor has approved and agreed to the amount in the claim. Finally in task 7, it is

the responsibility of the planning coordinator to monitor the payment from the main contractor. The planning co-ordinator is required to keep track of the PC panels' delivery status, claim status as well as the number of panels in the project. The tracking is manual and proved to be cumbersome and time-consuming process.

Figure 4-7 VSM for progress claim and payment – current workflow

The manpower requirement, average current processing time and wait time for each task are tabulated in Table 4-13.

Table 4-13 Present timing of progress claim and payment

No.	Task description	Role/ staff involved	Present workflow		
			No. of worker	Processing time (man-day/project)	Wait time (man-day/project)
1	Create panel list	Planning Co-ordinator	1	8.0	14.7
2	Update of casting record and delivery status	Planning Co-ordinator	1	3.5	4.5
3	D/O returns	Logistic Staff	1	0.7	5.0
4	Update claim progress	Planning Co-ordinator	1	3.0	5.7
5	Prepare monthly claim	Planning Co-ordinator	1	3.0	4.2
6	Prepare invoice	Finance staff	1	3.0	4.2
7	Monitor payment	Finance staff	1	1.5	10.0
Total			7	22.7	48.3

Table 4-14 summarises the value stream analysis results, the number of days needed to complete a single project on average is 71 man-days. Based on the results, approximately 32% of the total time is the value-added time and rest of the 68% is non value-added time.

Table 4-14 Present workflow - wait time and processing time

	Duration of current workflow (man-day/project)	Percentage of total (%)
Total wait time	48.3	68%
Total processing time	22.7	32%
Total time the for progress claim and payment	71	100%

4.3 Summary

This chapter presents the approach to determine the CSFs for BIM adoption. From the questionnaire survey, a total of eight CSFs was established. By placing the emphasis on CSFs, PC manufacturers can navigate towards higher levels of BIM utilisation. To further understand how these CSFs may contribute to productivity improvement, multiple regression was conducted and a total of four factors were shortlisted. Thus, the regression model called “PC-CSF performance analytical model” was established. Evidently, the CSFs for BIM adoption may be useful to bring PC manufacturers to higher technology utilisation, but not all CSFs contribute to improving the productivity of PC manufacturers.

To test the hypothesis and demonstrate the combined benefits of the PC-CSF performance factors bring to the PC supply chain, the three identified key workflows were meticulously mapped out and presented in this chapter. Namely, (1) approval of shop drawing for production, (2) tracking and delivery of inventory and (3) progress claim and payment. Every task in the workflows, including its current issues, were identified and carefully studied with the assistance of subject-matter experts from the selected PC manufacturer. The VSM/A technique was used to assist in the identification of possible improvement in the future state workflows.

Chapter 5 describes the development of the Production Logistic Management System (PLMS) to support the PC-CSF performance factors. Chapter 6 presents the productivity improvement brought about by the combined PC-CSF performance factors.

Chapter 5 : Development of the Production Logistic Management System to support the application of the PC-CSF performance factors

This chapter presents the development of the BIM cloud-enabled solution called the Production Logistic Management System (PLMS). It comprises three key modules, each serving the specify needs. Namely, (1) System for Shop Drawing Approval, (2) System for Inventory Tracking and Delivery and proof of delivery, (3) System for Progress Claim and Payment. Every module can function as a standalone solution or combined to support the application of the PC-CSF performance factors. Designed with lean practice in mind, the PLMS system also provides a common data environment for data hosting and information sharing.

5.1 Overview of the Production Logistic Management System (PLMS)

The purpose-built PLMS system is to support the application of the PC-CSF performance factors. It comprises three key modules. (1) System for Shop Drawing Approval (SSDA), (2) System for Inventory Tracking and Delivery (SITD) and Proof of Delivery (POD), (3) System for Progress Claim and Payment (SPCP). Each module is designed to serve the identified key workflows, namely (1) approval of shop drawing for production, (2) tracking and delivery of inventory and (3) progress claim and payment. The functions of each module are discussed in appendix E.

5.1.1 System for shop drawing approval (SSDA) for production

The main contractor provides construction drawings from the designers to the PC manufacturer. The PC manufacturer will further develop the designer's intent into constructible BIM model.

Figure 5-1 Shop drawing generation from BIM model

Figure 5-1 shows the typical process of shop drawing generation from the constructible BIM model at level of development (LOD) 400. To create a constructible BIM at LOD 400, the PC manufacturer needs to address fabrication issues such as lifting position, maximum transportation weight, penalisation, as well as design inconsistencies. The BIM model should also include complete information for fabrication and assembling such as quantity, size, shape, location, and other essential details (BIMForum, 2019). Then, from this BIM model, precast shop drawings can be automatically generated. As the drawing generation process is totally automatic, any change made on the BIM can be instantly reflected on the drawings, thus tremendously reducing the time spent on drawing revising and updating.

The SSDA facilitates information sharing among stakeholders in the project. This enhances cooperation and help smoothen the overall shop drawing approval workflow. The functionality of the SSDA system is illustrated in Figure 5-2. There are four key functions, they are: (1) master drawing list, (2) transmittal, (3) grouping, and (4) sync folder. As the project progresses, the MDL (a list that tracks the revision of each shop drawing submitted for review) is updated accordingly.

1. **Shop drawings.** From the perspective of the PC manufacturer, the BIM cloud-enabled system becomes a central repository of shop drawings. This allows users to make changes to the shop drawings, so that the latest revisions are made available real-time for the respective groups within the organization. Similarly, the shop drawings can be shared with external parties such as main contractors and consultants. They can access the system to respond to shop drawing approval requests of the PC manufacturer effectively and efficiently.
2. **Sync all files.** This function allows user to synchronise the latest approved shop drawings that are uploaded to SSDA by the main contractor to the MDL. Users can then manage the revisions and update the PC production department accordingly.

Figure 5-2 Functionality of SSDA

3. **Grouping.** This function allows PC manufacturer to categorise the various components into specific groups. Each group represents a type of PC panels. For instance, group name: ‘CO’ is column, ‘BA’ is bay window and so on. Grouping prepares the PC manufacturer for batch production.
4. **Transmittal.** Transmittals are often used in construction companies as a necessary communication tool in projects. The SSDA can generate transmittals along with packages of document for transfer. It is a formal means of sending shop drawings, models and other documents to another project member within the company or to external parties (e.g., main contractor).

5.1.2 System for Inventory Tracking and Delivery (SITD)

The System for Inventory Tracking and Delivery (SITD) provides user effective information access to locate, retrieve and deliver PC panels. For the purpose of this research, the development focussed on tracking five statuses that are critical to the PC manufacturer. Namely, (1) “Manufactured”, after the final inspection. (2) “In-transit”, delivery initiated by PC manufacturer. (3) “Delivered”, item received by main contractor. (4) “Rework”, item rejected by main contractor, and (5) “Installed”, PC panels erected on site. They were deemed critical because the progress claim and payment depend on the completion of these statuses. For instance, the main contractor will not approve the claim and pay in full unless the specific PC panel’ status is indicated as “Delivered”. By means of RFID technology and colour coding technique, the progress status of each panel is tracked and recorded on the BIM cloud platform. Specific colour can be assigned to represent each status as shown in Figure 5-3.

Figure 5-3 Colour coding PC panel progress status

The functionality of the SITD system is shown in Figure 5-4. There are three key functions, they are: (1) production scan, (2) post-production scan and (3) PC panel enquiry. As the project progresses, the status of each PC panel is captured in real-time.

1. **Production scan.** There are three progress statuses to be tracked: (1) “Manufactured” status, which is essential for progress claim and payment purpose, (2) “In-transit” indicates that delivery of the PC panel has initiated. This task is planned according to the general erection sequence to minimise unnecessary site storage handling, and (3) “Rework” status, indicates the PC panel needs attention (e.g., PC panel rejected due to quality issues).

Figure 5-4 Functionality of SITD

2. **Post-production scan.** There are two progress statuses: (1) “Delivered” status indicates that the PC panel has delivered on site and the recipient signed-off. This is an essential step for progress claim and payment purpose. To acknowledge the delivery, Proof of Delivery (POD) system is used. More details of POD in the following section. (2) “Installed” indicates that the PC panel has been erected.
3. **PC panel enquiry.** The progress status and location of each PC panel can be obtained in real-time. The user can either query on the 3D IFC data model or search the PC panel by its UID. Key information such as element type, last progress status and storage location are retrieved for further actions.

Proof of Delivery (POD) is an essential and final step to automate the delivery process. With POD, the recipient can acknowledge the delivery of PC panel digitally, eliminating any manual tracking, saving both time and efforts of the PC manufacturer and the main contractor. In addition, PC manufacturer and the project stakeholders can get real-time update of the delivery status. This prevents disputes between organisations and reduce the time taken for payment processing as the delivery status can be obtained via the BIM cloud-enabled system.

Since POD acts as a document that confirms receipt of an item, recipients must digitally sign for receipt when the item arrives. The typical delivery process is described below. Referring to Figure 5-5,

- At the PC factory, once the PC panels are loaded and the RFID tags scanned, the transporter will acknowledge the completion of the loading process by a sign-off. The D/O is then automatically generated.
- Upon receipt of the PC panel at the construction site, the recipient then sign-off with a photo of the item as Proof of Delivery.
- The “completed” status of delivery information is stored in the BIM cloud platform. A copy of the proof of delivery receipt is then sent to the main contractor, together with the delivery order.

The POD system can also be used to track the transporter activities to ensure accountability. By digitising the whole delivery process, it eliminates unnecessary paperwork from the operation.

Figure 5-5 Functionality of POD

5.1.3 System for Progress Claim and Payment (SPCP)

A construction project is known for its huge number of claims which increases proportionally with time. The claim process can be very complex as it involves many parties across different departments within the PC manufacturer. They also need to work meticulously with the main contractor to ensure timely and accurate payments are received. In an ideal situation, after the PC manufacturer has issued a payment claim, the amount claimed should be paid by the main contractor on or before the due date. However, if there is any dispute about the claim, or part of the claim, the payment will likely be delayed.

This research proposes a system to support the documentation of claims, resolve the time consuming manual process, and importantly to share the claim status among the stakeholders to mitigate delays. The functionality of the purpose-built solution called System for Progress Claim and Payment (SPCP) is shown in Figure 5-6. There are two key functions, they are: (1) claim setting and (2) claim and payment.

1. **Claims setting.** The claim amount is set according to one of the two scenarios, (1) Stage payment. Claim made in respect of a milestone completion, i.e., first payment upon manufactured and the balance is paid after delivered or (2) full payment upon delivery. The typical claim is by volume of concrete cast (e.g., in m^3) multiple by the industry prevailing rate (e.g., in \$). On a monthly basis, claim reports may be generated for payment approval by the main contractor. Only when the main contractor has agreed to the claimed amount, the PC manufacturer can then officially submit the claim for processing.

Since the BIM model provides reliable and accurate quantities such as the concrete volume of respective panels, the SPCP system can extract the panel details from the model for progress claim calculations. For instance, Figure 5-7 shows the plank in three-dimension, information pertaining to this panel such as the amount of concrete volume used of 0.962m^3 , can be easily extracted from BIM model. Instead of utilising the spreadsheet, PC manufacturer can build up their claims list from the parametric model.

Figure 5-6 Functionality of the SPCP

Figure 5-7 Quantity take-off with BIM

2. **Claim and payment.** This function comprises two sub-functions, namely (a) prepare claim and (b) update claim.
 - a. Prepare claim. The payment term can be in one of the two set conditions (1) Stage payment. First payment is made when the PC panel is manufactured, and the balance is paid after it is delivered (typically on a 70% and 30% proportion) or (2) Full payment after delivery of the PC panel. Referring to Figure 5-6, the SPCP system allows the PC manufacturer to submit the progress claims by selecting the PC panels from the list of panels that are of the status “manufactured” or “delivered”. The claim is then routed to the PC manufacturer’s approving officer (i.e., supervisor or manager) for approval before reaching the main contractor. Once the claim has been approved by both parties, it is digitally signed and a notification email is sent to all parties involved. If the claim is rejected, it will be routed back to the PC manufacturer for amendment before re-submission.
 - b. Update Claim. The system can automatically generate the progress claim form, claim summary or printed reports when required. User can monitor the claim status via the SPCP system and a reminder email will be automatically triggered when a payment response (i.e., claim approved or rejected) has not been received from the main contractor after two weeks. Section 5.2.3 further illustrates the value-add of the SPCP system to the progress claim and payment workflow.

5.1.4 The status dashboard

A purpose-built web-based dashboard was developed to provide crucial information of any construction project. The dashboard provides the PC manufacturer and its stakeholders a comprehensive snapshot of the status of the on-going project in real-time.

Figure 5-8 Functionality of the dashboard

As shown in Figure 5-8, there are three key functions, they are: (1) status and element type setting, (2) visualisation, (3) inventory enquiry and (4) reports.

1. **Status and element type setting.** The dashboard setting function allows user to control key aspects of the dashboard. Figure 5-9 shows the PC panel colour coded according to its progress status, e.g., the “Delivered” status is colour coded in green. As different projects constitute different types of PC elements, the name of each element can be customised as shown in Figure 5-10, e.g., “B” to represent beam and “CL” to represent column..

Manage Status		
STATUS 1	☒	Manufactured
STATUS 2	☒	In-Transit
STATUS 3	☒	Delivered
STATUS 4	☒	Installed
STATUS 5	☐	

Color coding for the status entries:

- STATUS 1: SkyBlue
- STATUS 2: Tomato
- STATUS 3: LightGreen
- STATUS 4: MediumPurple
- STATUS 5: Gray

Figure 5-9 PC progress status with colour coding

Manage Object Type	
TYPE	Precast
TYPE 1	B
TYPE 2	CL
TYPE 3	FF
TYPE 4	FP
TYPE 5	L

Object type settings:

- TYPE 1: Beam
- TYPE 2: Column
- TYPE 3: Facade Fin
- TYPE 4: Facade Panel
- TYPE 5: Ledge

Figure 5-10 Element type setting

2. **Visualisation.** At the most basic level, the dashboard provides 3D visual, real-time representation of a project's data. It enables users to access quickly and easily to monitor and generate project insights. The IFC data model enables stakeholders to view the project from different vantage point allowing a better understanding of spatial relationships between building components.
3. **Inventory enquiry.** PC panels can be stored either at the factory or a temporary storage yard. Upon request, the logistic department needs to locate and retrieve the PC panels swiftly so that delivery can be done on time. This function allows users to search the location of each PC panel based on its unique identification or from the IFC data model.
4. **Reports.** The dashboard provides the PC manufacturer full visibility into the shop drawing approval status as well as the status of each claim submitted. Incidentally, claim reports may be generated for payment approval by the main contractor.

5.2 Application of the PLMS system

Over a period of 12 months, the selected PC manufacturer has completed a total of 22 projects, with contract values ranging from S\$10 million to S\$35 million. The author has selected a 9-storey mid-sized nursing home precast project in Singapore to demonstrate the capabilities of PLMS system. The total contract value is estimated at S\$20 million with precast panels constituting approximately 75% by volume of the entire structural concrete used during the construction stage. The precast panels start from level-2, with 320 panels per floor, ranging from beam, slabs, columns, beams and façade to be identified, tracked, and located in real-time. Each of the three modules within the PLMS, namely SSDA, SITD and SPCP were applied to the three key workflows.

The subject-matter-experts from the respective departments were introduced to the systems co-developed by both the PC manufacturer and the author. Hands-on opportunities were also provided to gather expectation from the subject-matter experts. They have in-depth knowledge of the respective workflows, therefore it was possible for them to validate the productivity improvement that the systems bring to the key workflows.

5.2.1 The pre-production phase

During the pre-production phase, the activities include project scope of work briefing, master schedule alignment and contract budget confirmation. It is followed by project kick-off meeting, whereby a project team needs to clarify and confirm submissions protocol, M&E provisions onto the precast panels and drawing numbering system with the main contractor. The key workflow of this phase is the shop drawing approval process. Production will not commence until the required shop drawings have been approved by the consultant through the main contractor (typically appointed as the primary contact). Referring to Figure 5-11,

1. The main contractor provides the latest construction drawings to the PC manufacturer.

Figure 5-11 Digitised the approval of shop drawings workflow

2. The PC manufacturer studies the construction drawings and further develops the designer's intent into constructible BIM model. Figure 5-12 shows the detail of the BIM model of the nursing home project. Multiple updates of the model are expected as discussions and clarification continue with the main contractor.

Figure 5-12 BIM model of nursing home project

For this project, the quantity take-off was performed using the BIM model, Table 5-1 provides a summary of the panel list, and a total of 1,352 PC panels had to be cast.

Table 5-1 Precast elements to be cast for the nursing home project

PC panels	Number of panels
façade	143
Beam	440
Ledge	55
Slab	514
Column	52
Wall	148

3. In the process of building up the constructible BIM model, the PC manufacturer addresses any fabrication issues such as consideration on lifting position, maximum transportation weight and size, penalization, and highlighting any design inconsistencies. Shop drawing of each identical precast element is subsequently generated from the BIM model. Figure 5-13 shows the shop drawing of the slab. Similarly, the master drawing list (MDL) can be generated at any time to reflect the up-to-date shop drawing approval status.

Figure 5-13 Shop drawing generated from BIM model

4. The shop drawings were uploaded to SSDA. For this project, approximately 300 shop drawings were needed to be approved and tracked across the entire construction phase. Within that duration, change orders were expected. As such, revision tracking became critical. The SSDA facilitates information sharing among stakeholders. This enhances their cooperation, thus helping to smoothen the overall shop drawing approval process.

5.2.2 The production phase

For the purpose of this research, the progress of each PC panel is tracked along five key statuses, namely (1) “Manufactured”, after the final inspection. (2) “In-transit”, delivery initiated by PC manufacturer. (3) “Delivered”, item received by main contractor. (4) “Rework”, item rejected by main contractor. And (5) “Installed”, PC panel erected on site. The tracking is achieved by assigning each PC panel with a unique identity RFID tag. Once the tag is scanned, the relevant information is uploaded to the PLMS system.

Figure 5-14 shows the screenshot of the PC panels’ progress status. For instance, the total number of beams to be cast is 440 panels, of which 97 panels are manufactured (22%), 11

panels (or 12%) are in the process of delivery and 8 panels have been received by the main contractor.

Figure 5-14 The status of PC panels

5.2.3 The post-production phase

The post-production phase comprises two key workflows: (1) the tracking and delivery of inventory and (2) the progress claim and payment.

Delivery of panels is planned according to the general erection sequence to reduce storage and handling. At the construction site, the contractor also needs to track the delivery of components so that they may install them as scheduled. For this process to be effective, each panel needs to be identified, tracked and located as soon as it is cast.

The tracking of inventory: the SITD system allows the PC manufacturer to easily access and view the inventory status so that users can locate, retrieve and deliver the PC panels efficiently and on time. The use of RFID together with SITD system tracks each PC panel's status in real-time throughout the entire construction phase. Figure 5-15 shows the 3D model of nursing home project via the dashboard.

The status and location of any PC panel can be obtained:

1. From the 3D model. The system enables direct and easy visualisation of PC panels and their status by using colour coding technique. All parties can access the progress

status of any PC panel simply by recognising the colours, so that appropriate actions or decisions may be taken.

2. By PC panel unique identity. The storage location can be either at the precast factory or the temporary occupation licence (TOL) area. The search can be done by the panel unique identity. The logistic staff can then retrieve the PC panel accordingly.

Figure 5-15 Tracking of PC panel of the nursing home project

The delivery of inventory: the proof-of-delivery (POD) system digitises the delivery process and eliminates unnecessary paperwork from the operation. Referring to Figure 5-16, the delivery workflow involves the POD system that comprises three key functionalities, (1) PC manufacturer sign-off (item ready to ship), (2) the main contractor sign-off (item received) and (3) storage of digitised D/O.

Figure 5-16 Digitised the delivery workflow

1. PC manufacturer sign-off. Acknowledge the completion of the loading process and that it is ready to ship out. Items to be delivered are scanned, and the PC panels' identities are indicated in the handheld device.
2. The main contractor sign-off. Having received the PC panels, the recipient signs-off to indicate that the items have been delivered and each item is scanned and updated onto the system as "received".
3. Storage of digitised D/O. All information relating to the delivery is stored in the cloud-based system for future retrieval, mainly for the purpose of progress claim and payment.

The progress claim and payment: at a stipulated time, the progress claim starts soon after the first batch of PC panels has been delivered. The steps are shown in Figure 5-17, (1) once the quantity take-off process is completed, the SPCP system then takes over the remaining three steps, namely (2) claim calculations, (3) claim submission and (4) summary reporting.

1. BIM model for quantity take-off. The creation of panel list is an essential step towards the claim preparation. Quantity take-off allows the company to extract the material usage information of PC panels. The SPCP system extracts information readily available from the BIM model to generate the panel list.
2. Claim calculations. The status of each PC panel is stored in BIM cloud-enabled system. This allows the planning co-ordinator to automatically keep track of the PC

panel delivery status and submit the progress claim on time. The SPCP system calculates and updates the claim list and the amount, based on the following conditions:

- The claim amount is calculated based on the type rate (unit price) and the payment schedule (criteria) as approved by the main contractor. Typically, the payment term goes according to one of the two set conditions (1) Stage payment. First payment upon manufactured, and the balance is paid after delivered (typically on a 70% and 30% proportion) or (2) Full payment after delivery of the PC panel. In the case of the nursing home project, the stage payment term was implemented.

Figure 5-17 Digitised the progress claim and payment workflow

- The PC manufacturer may make a claim if the main contractor has approved their claim request. And in the case of criteria (1), the balance amount has to be substantiated with signed delivery orders.
 - The variance between the previous claim and actual amount received can be accrued to the subsequent claim. This process will continue until the amount is tallied.
 - Retention is taken into account in the calculation of each progress claim, according to the project contract requirement.
3. Claim submission. The claim submission period is typically scheduled at the end of each month. Figure 5-18 shows the screenshot of the list of PC panels (i.e., beam) given to the department manager for approval before submitting to the main contractor. As per the agreement, the PC manufacturer may claim 70% of the total PC panel cost upon manufactured.

TYPE	ELEMENT TYPE	STATUS	NAME	UNIT VALUE	RATE (\$)	AMOUNT (\$)	CLAIM %
Precast	Beam	Manufactured	2HPB39	150.00	\$65.10	\$6,835.50	70%
Precast	Beam	Manufactured	2HPB40	150.00	\$65.10	\$6,835.50	70%
Precast	Beam	Manufactured	2HPB41	150.00	\$65.10	\$6,835.50	70%

STATUS LOG:

1. Submitted by Thomas on 11/05/2020 16:10:21
2. Rejected by ThomasPC on 12/05/2020 14:30:12
3. Submitted by ThomasPC on 12/05/2020 14:30:33
4. Rejected by ThomasPC on 12/05/2020 14:30:16
5. Submitted by Thomas on 24/05/2020 16:03:44

REPORTS:

- Overall Summary
- Breakdown Summary
- Elements Information
- Progress Claim Form
- Progress Claim Summary
- Payment Response Summary

DELIVERY ORDER:

No DO yet

Figure 5-18 The nursing home project claim submission

4. Summary reports. Different level of reporting can be achieved with SPCP system. The claim information may be viewed directly through the dashboard or exported to spreadsheet for further processing. Figure 5-19 provides an example of the summary of claims exported to spreadsheet format. At any point in time, claim reports may be generated for payment approval to the main contractor.

2											
3	TYPE	ELEMENT TYPE	NAME	WEIGHT	LENGTH	HEIGHT	WIDTH	VOLUME	RATE	CLAIMED %	AMOUNT
10	Precast	Beam	2HB27A	0	0	0	0	5.7	65.1	70%	\$260
11	Precast	Beam	2HB27A	0	0	0	0	5.7	65.1	30%	\$111
12	Precast	Beam	2LPB3	0	0	0	0	5.7	65.1	70%	\$260
13	Precast	Beam	2LPB3	0	0	0	0	5.7	65.1	30%	\$111
14	Precast	Beam	2LPB3A	0	0	0	0	5.7	65.1	70%	\$260
15	Precast	Beam	2LPB3A	0	0	0	0	5.7	65.1	30%	\$111
16	Precast	Beam	2VPB1	0	0	0	0	5.7	65.1	70%	\$260
17	Precast	Beam	2VPB1	0	0	0	0	5.7	65.1	30%	\$111
18	Precast	Beam	2VPB10	0	0	0	0	5.7	65.1	70%	\$260
19	Precast	Beam	2VPB10	0	0	0	0	5.7	65.1	30%	\$111
20	Precast	Beam	2VPB11	0	0	0	0	5.7	65.1	70%	\$260
21	Precast	Beam	2VPB11	0	0	0	0	5.7	65.1	30%	\$111
22	Precast	Beam	2VPB12	0	0	0	0	5.7	65.1	70%	\$260
23	Precast	Beam	2VPB12	0	0	0	0	5.7	65.1	30%	\$111
24	Precast	Beam	2VPB13	0	0	0	0	5.7	65.1	70%	\$260
25	Precast	Beam	2VPB13	0	0	0	0	5.7	65.1	30%	\$111
26	Precast	Beam	2VPB15	0	0	0	0	5.7	65.1	70%	\$260
27	Precast	Beam	2VPB15	0	0	0	0	5.7	65.1	30%	\$111
28			SUB TOTAL								\$3,340

Figure 5-19 Example of progress claim report

5.3 Summary

In this chapter, the development of the respective modules of the PLMS system were introduced, namely (1) System for Shop Drawing Approval (SSDA), (2) System for Inventory Tracking and Delivery (SITD) supported by Proof of Delivery (POD) and (3) System for Progress Claim and Payment (SPCP). To illustrate the capabilities of the PLMS system, a typical mid-size precast project was selected and the functionalities of each module were discussed with the subject-matter-experts from the respective departments. The BIM cloud-enabled system is developed to support the PC-CSF performance factors when applied to the case studies. It is pivotal to the productivity enhancement of the newly developed workflows.

Chapter 6 : Application of the PC-CSF performance factors

This chapter demonstrates the usefulness of the PC-CSF performance analytical model (which comprises four factors) in real-world scenarios by means of case studies on the PC supply chain. At the same time, the hypothesis H₉ “The combined benefits of the PC-CSF performance factors could greatly improve the productivity of key workflows in the PC supply chain” was tested. The PC-CSF performance factors were applied to three case studies. These key workflows in the PC supply chain are (1) approval of shop drawing for production, (2) tracking and delivery of inventory and (3) progress claim and payment. Supported by the purpose-built BIM cloud-enabled system called the Production Logistic Management System (PLMS), the productivity improvement was obtained by comparing the current-state workflows with the newly developed workflows.

6.1 Analysis and determination of productivity improvement for key workflows in the PC supply chain

To demonstrate and validate the usefulness of the PC-CSF performance factors, a hypothesis H_9 was formulated as presented in section 3.4.1. The author then carried out the following steps to apply the PC-CSF performance factors to the three case studies, namely Case 1 - approval of shop drawing for production workflow, Case 2 - tracking and delivery of inventory workflow and Case 3 - progress claim and payment workflow.

The PC-CSF performance factors were first translated into actionable items as discussed in Table 3-6. The actionable items of the four factors were then applied in combination to each of the three workflows. As presented in section 3.4.6, three likely outcomes can be expected when the PC-CSF performance factors are applied collectively, they are: (1) task eliminated, the specific task was removed from the current workflow due to full automation, (2) task optimised, the specific task was improved. Under such circumstances, the subject-matter-experts were asked to estimate the percentage of improvement. And (3) not applicable or N.A., typically these were tasks that involve physical or manual works, as such transportation of the PC panel. To visualise the improvement, VSM is used to display the newly developed workflows (see Figure 4-4 for explanation of VSM symbols) and the factors' contributions to the improvements of each task are explained. The three outcomes are represented by the boxes as shown in Figure 6-1.

Figure 6-1 Expected outcomes

Section 6.1.1 to 6.1.3 discuss the application of the four PC-CSF performance factors and the productivity improvement these factors bring to the three key workflows. The productivity gained is compared between the “average values” of the current-state workflow and “expected values” of the newly developed workflow. The results determine if the hypothesis H_9 should be accepted or rejected.

6.1.1 Case 1 - Approval of shop drawing for production

Figure 6-2 illustrates the actions taken to test the hypothesis H₉ and demonstrate the usefulness of the combined PC-CSF performance factors on Case 1. The contributions of these factors to the productivity improvement of the approval shop drawing workflow are described below.

Factor 1: Constructible BIM. The PC manufacturer studies the construction drawings and further develops the designer's intent into constructible BIM model at LOD 400. As illustrated in section 5.2.1, the use of BIM model has helped (1) address any fabrication issues or design inconsistency at the pre-production phase, eliminating errors in casting which can be costly if left unchecked. (2) It allows accurate extraction of the panel list for the creation of MDL which is used to monitor the drawings approval status (see appendix E). (3) It mitigates the problem of drawing version management. In other words, any changes done in the model is automatically incorporated to the drawings which drastically reduces the time taken for drawings generation and updating.

Factor 2: Top management commitment. The active involvement and participation of top management were the prerequisites for this research. (1) Future-state vision and guidelines were set and discussed at the beginning of this study to all responsible parties in the design department. And (2) the active participation and interaction with the subject-matter-experts from the design department has led to an in-depth understanding of the approval of shop drawing workflow. See appendix D for detail.

Factor 3: Team coordination. By mean of in-depth interviews with the respective subject-matter-experts from the design department, (1) explicit information such as procedural data (refer to Table 3-8) and time data (refer to Table 3-11) were collected accordingly. (2) Current practices and issues that impede team coordination were also identified and recorded. For instance, manual tasks to create, monitor and update of MDL (see Table 3-8) that led to the use of outdated shop drawings. (3) The corresponding BIM cloud-enabled system called System for Shop Drawing Approval (SSDA) was developed to help mitigate and improve the productivity of the shop drawing approval process. Section 5.1.1 discussed the SSDA system in detail.

Figure 6-2 Application and analysis of PC-CSF performance factors on Case 1

Factor 4: Information sharing. The SSDA system was also developed to facilitate information sharing among stakeholders. The BIM cloud-enabled system becomes a central repository of shop drawings. This allows users to maintain the shop drawing revisions from one source and allows the shop drawings to be easily shared among stakeholders at any time. In replacement of the manual transmittal process, the SSDA allows the user to generate transmittals along with packages of document for transfer to another project member within the company or to external parties, thus streamlining team coordination. See appendix E for detail.

As depicted in Figure 6-3, the application of the PC-CSF performance factors supported by the System for Shop Drawing Approval (SSDA) has brought about the following improvement to the approval of shop drawing workflow. The initial three tasks (Task 1 to Task 3) require the tacit knowledge of the subject-matter experts to study the construction drawings to further develop the designer's intent into constructible BIM model. It has to be checked and verified by the engineer before generating the MDL. As mentioned in the previous section, BIM is utilised to address any fabrication or design issues so that clarification can be made with the main contractor (see section 4.2.1) before subsequent steps are taken. It is then utilised to generate the panel list for the creation of MDL (Task 4), as well as the PC panel shop drawings. However, due to the nature of the MDL creation process, human intervention is still required (e.g., manual step of digitising the shop drawings into a format that is acceptable by the main contractor). As such Task 4 can only be partially optimised. Nevertheless, the processing time of this task has been drastically reduced (processing time saved, from 3 to 0.5 man-day).

The deployment of the SSDA system has enhanced the information sharing between the PC manufacturer and the main contractor. It allows digitised shop drawings (instead of hardcopies) to be shared via the BIM cloud-enabled system. For this reason, the sending of shop drawings to the main contractor (Task 5) for review has substantially improved (processing time saved, from 2 to 0.1 man-day). In other words, once the transmittal is received by the main contractor, they can access the SSDA system anytime to view and approve the shop drawing stored in the BIM cloud. Once the shop drawing is approved, the approval status and drawing version are automatically updated on the MDL, eliminating the manual tasks to monitor (Task 6) and update (Task 7) the MDL.

Figure 6-3 VSM for approval of shop drawing – newly developed workflow

The above-mentioned improvements were discussed and verified with the top management of the selected PC manufacturer and main contractor. Section 5.1.1 discusses the SSDA system in detail. The following sections discuss the productivity improvement of the newly developed workflow.

Productivity improvement measurement

Overall, the lead time in the newly developed workflow is reduced by eliminating or optimising four out of the seven tasks. Furthermore, it has also reduced the number of workers from 13 to 11, or 15% saving in manpower across the entire workflow. The tasks of the newly developed workflow are tabulated in Table 6-1.

Table 6-1 Summary of timing - newly developed approval of shop drawing workflow

No.	Task description	Role/ staff involved	Newly developed (future-state) workflow			Outcome
			No. of worker	Processing time (man-day/ project)	Wait time (man-day/ project)	
1	Study of drawings	Design engineer	1	7.5	14.7	N.A. ²
		Draftsman	3			
		Planning co-ordinator	1			
2	Preparation of shop drawings	Draftsman	3	4.2	9.6	
3	Check by engineer	Design engineer	1	0.8	4.2	
4	Manual creation of MDL	Draftsman	1	0.5	1.0	50% optimised ¹
5	Shop drawings send to MC	Draftsman	1	0.1	0.5	90% optimised ¹
6	Manual monitoring of MDL	-	-	-	-	Eliminated
7	Manual update of MDL	-	-	-	-	Eliminated
Total			11	13.1	30.0	

¹ Percentage of improvement – as per experts' view.

² N.A. – not applicable tasks

The time data for the current workflow (refer to Table 4-9) was compared with the data for the newly developed workflow (refer to Table 6-1). As illustrated in Figure 6-4 and Figure 6-5, the processing time and wait time of Task 4 to Task 7 have been eliminated or reduced with the application of the PC-CSF performance factors supported by the SSDA system.

Figure 6-4 Case 1 - Processing time of current vs newly developed workflow

Figure 6-5 Case 1 - Wait time of current vs newly developed workflow

Table 6-2 provides a summary of the productivity gain of the approval of shop drawing workflow brought about by applying the PC-CSF performance factors. The duration of the current workflow is obtained from Table 4-10. By reducing the total time of current workflow from 68 man-days to 43 man-days, the PC manufacturer was able to improve the approval of shop drawing process by 37%. Also, the processing time and wait time have improved by 41% and 35% respectively. The results have clearly shown that the PC-CSF performance factors can effectively enhance the workflow and brings forth substantial productivity improvement. As such, the hypothesis H_9 , i.e., the combined benefits of the PC-CSF performance factors could greatly improve the productivity of key workflows in the PC supply chain is supported.

Table 6-2 Productivity gain for case 1

	Duration of current workflow (man-day/project)	Duration of newly developed workflow (man-day/project)	Improvement (%)
Total wait time	46	30	35%
Total processing time	22	13	41%
Total time for approval of drawings	68	43	37%

6.1.2 Case 2 - Tracking and delivery of inventory

Figure 6-6 illustrates the actions taken to test the hypothesis H_9 and demonstrate the usefulness of the combined PC-CSF performance factors on Case 2. The contributions of these factors to the productivity improvement of the approval shop drawing workflow are described below.

Factor 1: Constructible BIM. The use of BIM model can help (1) to assign each PC panel with a unique identity (UID) RFID tag. Once the tag is scanned, the relevant information is uploaded to the purpose-built SITD system. Key information such as element type, last progress status and storage location are retrieved for further actions. In order to share and allow different project parties to access this information, (2) the BIM model can be exported to IFC data model that reside in the BIM cloud. The progress status of each PC panel can be obtained in real-time for better team coordination during the construction phase. The user can either query on the IFC data model or search the PC panel by its UID. By combining the benefits of RFID technology and colour coding technique, (3) the progress status of each panel can be visualised via the IFC data model as discussed in section 5.1.2 and illustrated in section 5.2.3.

Factor 2: Top management commitment. Similar to case 1, the active involvement and participation of top management was essential to this part for the research. (1) Future-state vision and guidelines were set and discussed at the beginning of this study to all responsible parties in the planning, production and logistic departments.

Figure 6-6 Application and analysis of PC-CSF performance factors on Case 2

And (2) the active participation and interaction with the subject-matter-experts were expected, which led to an in-depth understanding of the tracking and delivery of inventory workflow. See appendix D for detail.

Factor 3: Team coordination. By mean of in-depth interviews with the respective subject-matter-experts from the three key departments, i.e., planning, production and logistic, (1) explicit information such as procedural data (refer to Table 3-9) and time data (refer to Table 3-12) were collected accordingly. (2) Implicit information such as current practices and issues were also identified and recorded. As discussed in section 4.2.2, due to the lack of tracking capability in the current workflow, the PC panel location information is recorded manually into a spreadsheet. Such practices give rise to substantial amount of resources and time spent in locating the PC panel. This inevitably increases unnecessary costs which proves counter-productive. (3) The use of RFID together with the SITD system tracks each PC panel's status in real-time throughout the entire construction phase. This improves the team coordination as project participants can access and gain visibility of the progress status of any PC panel through the SITD system (see section 5.1.2).

Factor 4: Information sharing. The SITD when used together with POD system, enable the project participants to obtain real-time updates of the delivery status. With the POD system, the D/O is digitised and stored in BIM cloud-enabled system. As such the delivery status information can be easily shared among stakeholders at any time, replacing the error prone manual process as described in section 4.2.2. This prevents disputes between organisations and reduces the time taken for payment processing. Section 5.1.2 and section 5.2.3 described the delivery process in detail.

As depicted in Figure 6-7, the application of the PC-CSF performance factors supported by the System for Inventory Tracking and Delivery (SITD) with the Proof of Delivery (POD) system has brought about the following improvements.

Figure 6-7 VSM for tracking and delivery of inventory – newly developed workflow

The assignment of storage location (Task 1) and moving of panel to assigned location (Task 2) require manual and physical human intervention. Therefore, the same is expected for the future-state workflow. As discussed in section 5.1.2, a unique identity generated from the BIM model has been utilised to tag and track each PC panel across the different phases of production. For this reason, the SITD is able to fully automate task 3 and the progress status of each panel can be accessed in real-time through the IFC data model that resides in the BIM cloud. Vital information such as panel name, delivery dates and current location can be retrieved easily, eliminating the manual and time-consuming panel status update and search process.

Upon receiving the delivery request (Task 4), the search for panel begins (Task 5). This task has been partially optimised for the following reason. While the SITD system provides immediate response to the search request (as the status of each PC panel is tracked real-time), a physical panel retrieval is still required by the logistic worker for delivery (processing time saved, from 2.0 to 0.5 man-day). The loading of the PC panel for delivery is a manual process (Task 6), however the generation of D/O (Task 7) is expected to be fully automated. As mentioned in the previous section, the POD system digitised and stored the D/O in the BIM cloud, eliminating paperwork from the operation. Once the PC panel is transported to the construction site and unloaded (Task 9), the receipt of the PC panel (sign-off) is done via the POD system. As such, the D/O return process (Task 10) is digitised and fully automated.

The above-mentioned improvements were discussed and verified with the top management of the selected PC manufacturer. The subject-matter-experts from the relevant departments, i.e., planning, production and logistic department, have analysed the newly developed workflow and have given their inputs. The information was also presented to the main contractor for discussion and verification.

Productivity improvement measurement

The tasks of the newly developed workflow are tabulated in Table 6-3. Besides the productivity improvement in man-days, the newly developed workflow has reduced the number of workers from 14 to 10, or 30% saving in manpower across the entire workflow.

Table 6-3 Summary of timing - newly developed tracking and delivery of inventory workflow

No.	Task description	Role/ staff involved	Newly developed (future-state) workflow			Outcome
			No. of worker	Processing time (man-day/ project)	Wait time (man-day/ project)	
1	Assign storage location	Production Staff	1	0.5	4.2	N.A. ²
2	Move panel to location	Planning Co-ordinator	1	0.5	4.2	
3	Update panel status	Logistic Staff	-	-	-	Eliminated
4	Receipt delivery request	Logistic worker	1	1.5	3.8	N.A. ²
5	Search panel	Production Staff	1	0.5	3.8	75% optimised ¹
		Logistic worker	1			
6	Load panel for delivery	Logistic worker	2	3.8	9.1	N.A. ²
7	Generate D/O	Logistic worker	-	-	-	Eliminated
8	Transport to site	Logistic worker	1	4.8	14.4	N.A. ²
9	Unload and sign-off	Planning Co-ordinator	1	1.0	4.2	N.A. ²
		Logistic Staff	1			
10	D/O returns	Planning Co-ordinator	-	-	-	Eliminated
		Logistic Staff	-			
Total			10	12.6	43.6	

¹ Percentage of improvement – as per experts' view.

² N.A. – not applicable tasks

The time data for the current workflow (refer to Table 4-11) was compared with the data for the newly developed workflow (refer to Table 6-3). Figure 6-8 and Figure 6-9 compare the processing time and the wait time of each task in the current and newly developed workflows. The application of the PC-CSF performance factors supported by the SITD and POD systems were able to eliminate or reduce the processing time of Task 3, Task 5, Task 7 and Task 10. Accordingly, the wait time of Task 3, Task 7 and Task 10 was also eliminated.

Figure 6-8 Case 2 - Processing time of current vs newly developed workflow

Although the processing time of Task 5 (searching of panel) has been optimised, it is of the opinion of the subject-matter-experts that the wait time for this task remains the same (i.e., 3.8 man-day). As mentioned in the earlier section, the SITD system may provide immediate response to a search request, however the time needed to physically search and retrieve the panel remains the same.

Figure 6-9 Case 2 - Wait time of current vs newly developed workflow

The productivity gained through the application of the PC-CSF performance factors is summarised in Table 6-4. The duration of the current workflow is obtained from Table 4-11. By reducing the total time of current workflow from 94 man-days to 56 man-days, the inventory tracking and delivery workflow has improved by 40%. Also, the processing time

and wait time have also improved by 43% and 39% respectively. The results have clearly shown that the PC-CSF performance factors can effectively enhance the workflow and brings forth substantial productivity improvement. As such, the hypothesis H_9 , i.e., the combined benefits of the PC-CSF performance factors could greatly improve the productivity of key workflows in the PC supply chain is supported.

Table 6-4 Productivity gain for case 2

	Duration of current workflow (man-day/ project)	Duration of newly developed workflow (man-day/ project)	Improvement (%)
Total wait time	72	43.6	39%
Total processing time	22	12.6	43%
Total time for tracking and delivery of inventory	94	56.2	40%

6.1.3 Case 3 - Progress claim and payment

Figure 6-10 illustrates the actions taken to test the hypothesis H_9 and demonstrate the usefulness of the combined PC-CSF performance factors on Case 3. The contributions of these factors to the productivity improvement of the progress claim and payment workflow are described below.

Factor 1: Constructible BIM. In the case of progress claim and payment, the use of BIM model enables (1) accurate quantity-take-off (material usage). Information such as concrete volume of respective panels can be extracted from the BIM model for claim calculation. This eliminates the time-consuming and error prone spreadsheet method. (2) The progress status of each PC panel is tracked in real-time using the UID provided by the BIM model. And since the status information is stored in BIM cloud-enabled system, this allows the planning co-ordinator to automatically keep track of the PC panel delivery status and submit the progress claim on time. Section 5.1.3 and 5.2.3 illustrate the value-add of the BIM model for progress claim and payment workflow.

Figure 6-10 Application and analysis of PC-CSF performance factors on Case 3

Factor 2: Top management commitment. The active involvement and participation of top management was essential to the success of this research. (1) Future-state vision and guidelines were set and discussed at the beginning of this study to all responsible parties across four departments, namely production, planning, logistic and finance. (2) The active participation and interaction with the subject-matter-experts from these departments have led to an in-depth understanding of the current progress claim and payment workflow as discussed in section 4.2.3.

Factor 3: Team coordination. By means of in-depth interviews with the respective subject-matter-experts from the respective departments, (1) explicit information such as procedural data (refer to Table 3-10) and time data (refer to Table 3-13) were collected accordingly. (2) Current practices and issues were also identified and recorded as recorded in Table 3-10. (3) For instance, the claim process involves different parties across various departments within the PC manufacturer. As discussed in section 5.1.3 and illustrated in section 5.2.3, the use of SPCP system has improved coordination between production, planning and logistic departments.

Factor 4: Information sharing. The SPCP system enables information sharing between the departments in the PC manufacturer and the main contractor. As illustrated in section 5.2.3, (1) the detail information of the submitted claim is readily available online. This enables the department manager to access and approve the submitted claim efficiently. Similarly, the main contractor may access the BIM cloud-enabled system to view and approve the claim. (2) The claim approval and payment status information can be easily shared in real-time, providing up-to-date information to all parties involved.

As depicted in Figure 6-11, the application of the PC-CSF performance factors supported by System for Progress Claim and Payment (SPCP) system has brought about the following improvement to the program claim and payment workflow. The utilisation of BIM model enables accurate quantity-take-off. It allows the user to accurately extract the panel list from the 3D model for claim calculation (Task 1). With the POD system in place, all delivery orders are digitised, captured and stored real-time in the BIM cloud-enabled system called SPCP. Therefore, the PC manufacturer can accurately tally the casting record with the delivery status (Task 2) and be able to submit the progress claims on time.

Figure 6-11 VSM for progress claim and payment – newly developed workflow

Since the D/O is digitised, its return status (Task 3) is updated real-time, this eliminates any paperwork mishandling which could delay claim submission. Task 4 can only be partially optimised as human invention is require, i.e., the planning co-ordinator is required to update the amount received from the main contractor into the SPCP system manually (processing

time saved, from 3.0 to 1.5 man-day). Similarly, in Task 5, the preparation of claim has to be initiated by the planning co-ordinator. The SPCP system will extract the panel detail (e.g., volume of concrete cast) from the model and calculate the claim amount automatically based on the agreed pricing and claim schedule from the main contractor. Nevertheless, substantial amount of time saving can be expected (processing time saved, from 3.0 to 0.6 man-day).

The preparation of invoice (Task 6) commences once the main contractor has approved and agreed to the claims. The approval status is obtained via the SPCP system and manually administered by the finance department of the PC manufacturer (which is beyond the scope of the SPCP system). Lastly, the monitoring of payment (Task 7) is automated. The claim status information is stored in the BIM cloud and can be accessed and viewed via the dashboard in real-time. New claims submitted can be monitored and tracked accordingly, and outstanding claims can be consolidated for further review with the main contractor and resubmitted as future claims by the finance staff.

The above-mentioned improvements were discussed and verified with the top management of the selected PC manufacturer. The subject-matter experts across the four departments (i.e., production, planning, logistic and finance) of the PC manufacturer, including the main contractor have analysed the newly developed workflow and given have their inputs.

Productivity improvement measurement

The tasks of the newly developed workflow are tabulated in Table 6-5. Besides the productivity improvement in man-days, the newly developed workflow has reduced the number of workers from 7 to 3, which is a 57% reduction in manpower.

Table 6-5 Summary of timing - newly developed progress claim and payment workflow

No.	Task description	Role/ staff involved	Newly developed (future-state) workflow			Outcome
			No. of worker	Processing time (man-day/project)	Wait time (man-day/project)	
1	Create panel list	Planning Co-ordinator	-	-	-	Eliminated

2	Update of casting record and delivery status	Planning Co-ordinator	-	-	-	Eliminated
3	D/O returns	Logistic Staff	-	-	-	Eliminated
4	Update claim progress	Planning Co-ordinator	1	1.5	5.7	50% optimised ¹
5	Prepare monthly claim	Planning Co-ordinator	1	0.6	4.2	80% optimised ¹
6	Prepare invoice	Finance staff	1	3.0	4.2	N.A. ²
7	Monitor payment	Finance staff	-	-	-	Eliminated
Total			3	5.1	14.1	

¹ Percentage of improvement – as per experts' view.

² N.A. – not applicable tasks

The time data for the present-state workflow (refer to Table 4-13) was compared with the data for the newly developed (future-state) workflow (refer to Table 6-5). Figure 6-12 and Figure 6-13 compare the processing time and the wait time of each task in current and newly developed (future-state) workflows. The application of the PC-CSF performance factors supported by the SPCP system were able to eliminate or reduce the processing time of Task 1 to Task 7, with the exception of Task 6. The preparation of invoice (Task 6) is manually administered by the finance department of the PC manufacturer.

Figure 6-12 Case 3 - Processing time of current vs newly developed workflow

However, the wait time of Task 4, Task 5 and Task 6 remains. According to the subject-matter-experts from the PC manufacturer, the wait time of these tasks are highly influenced by external factors. For instance, Task 4 (update claim progress) and Task 5 (prepare monthly claim) can only commence when the PC panel is delivered and the D/O is digitally captured. The completion rate of these tasks is dependent on the efficiency of the transport

service engaged. Similarly, Task 6 (preparation of invoice) depends on the response rate of the main contractor to approve the claim. For these reasons, the wait time of the three tasks are expected to remain the same.

Figure 6-13 Case 3 - Wait time of current vs newly developed workflow

The productivity improvement through the application of the PC-CSF performance factors is summarised in Table 6-6. The duration of the current workflow is obtained from Table 4-13. By reducing the total time of current workflow from 71 man-days to 19.2 man-days, the progress claim and payment workflow is improved by 73%. Also, the overall processing time and wait time have also improved at 77% and 71% respectively. The results have clearly shown that the PC-CSF performance factors can effectively enhance the workflow and brings forth substantial productivity improvement. As such, the hypothesis H₉, i.e., the combined benefits of the PC-CSF performance factors could greatly improve the productivity of key workflows in the PC supply chain is supported.

Table 6-6 Productivity gain for case 3

	Duration of current workflow (man-day/ project)	Duration of newly developed workflow (man-day/ project)	Improvement (%)
Total wait time	48.3	14.1	71%
Total processing time	22.7	5.1	77%
Total time the for progress claim and payment	71	19.2	73%

6.2 Summary

This chapter has demonstrated that the productivity of key workflows in the PC supply chain can be improved when the PC-CSF performance factors were applied collectively. The four PC-CSF performance factors have been proven useful when applied to the three cases studies, namely (1) approval of shop drawing for production, (2) tracking and delivery of inventory and (3) progress claim and payment.

By means of the VSM/A technique, the productivity improvement of the respective workflow was compared and analysed. The field results have confirmed that hypothesis H₉ “The combined benefits of the PC-CSF performance factors could greatly improve the productivity of key workflows in the PC supply chain” is supported. It is worth noting, the purpose-built BIM cloud-enabled system called Production Logistic Management System (PLMS) which comprises three key modules, (1) System for Shop Drawing Approval (SSDA), (2) System for Inventory Tracking and (3) Delivery (SITD) with Proof of Delivery (POD) system and System for Progress Claim and Payment (SPCP) played a pivotal role in productivity improvement of the PC supply chain.

Chapter 7 : Conclusion, discussion, recommendations, and future research

This chapter summarises the main findings and contributions of the research. Recommendations for the PC industry are given based on this study and suggestions for future research are also presented.

7.1 Conclusion

This research provides both academic and practical implication. By means of empirical studies, the CSFs that influence the success of PC manufacturers in the BIM adoption were identified for the first time. And factors that contribute directly to productivity improvement were also shortlisted. A total of eight CSFs have been identified to be the most important factors to BIM adoption. However, the regression model called “PC-CSF performance analytical model” has suggested that not all factors contribute directly to productivity improvement of the PC manufacturers. Based on the regression analysis, the following factors were: (1) constructible BIM, (2) Top management commitment, (3) team coordination and (4) information sharing.

To confirm the hypothesis H_9 and validate the usefulness of the PC-CSF performance analytical model in real-world scenarios, the PC-CSF performance factors were applied to real-world PC supply chain problems. Consequently, three key workflows in the PC supply chain have been identified as case studies, they were (1) approval of shop drawings for production, (2) tracking and delivery of inventory and (3) progress claim and payment. The results have confirmed that the combined application of the PC-CSF performance factors (supported by the purpose-built BIM cloud-enabled called PLMS) can bring about productivity improvement to the PC supply chain.

7.2 Research achievement and contribution

There were five main objectives of this research as presented in Chapter 1. The major findings are summarised in the next two sections.

7.2.1 Academic achievement

- 1. To establish a BIM adoption model from the perspectives of PC manufacturers to explain organisations’ BIM adoption status.**

A conceptual model of BIM adoption for PC manufacturers was established to explain organisations’ BIM adoption status. It may also serve as a guide for the PC manufacturers to upgrade themselves to become industry innovators. Although, there are many affecting factors that can facilitate the companies in terms of BIM adoption

to some extent, by placing the emphasis on CSFs, the companies may have a tendency accelerate towards a highest level of BIM utilisation and maturity in the grid chart.

2. To develop the PCBIM hexagon framework for the determination of the CSFs affecting BIM adoption.

A PCBIM hexagon framework was developed to identify the CSFs affecting BIM adoption from PC manufacturers' view. It consists of driving forces from six areas: government, eco-system, company, team, process and BIM software tool. A total of eight CSFs identified for PC manufacturers, namely (1) A1 – Government policies, (2) A5 – Competitive advantage, (3) B1 – The top management commitment, (4) D1 – Team coordination, (5) D2 – Information sharing, (6) D3 – Constructible BIM, (7) D5 – Drawing approval and (8) E5 – Local support.

3. To assess and identify the CSFs that directly contribute to productivity improvement to the PC manufacturers.

A PC-CSF performance analytical model was developed by means of multiple regression. A total of four factors from the list of CSFs were considered as influential to the improvement of productivity and the author has called these factors the “PC-CSF performance factors”. According to the regression coefficients (from the largest to the smallest), the factors are summarised below.

- a. *Constructible BIM* ($\beta = 0.266$). PC manufacturers can certainly improve their productivity by relying on the data-rich BIM model to address any precast fabrication issues such as consideration on lifting position, maximum transportation weight and size, penalisation, and highlighting any design inconsistency.
- b. *Top management commitment* ($\beta = 0.243$). The top management behaviour and actions performed to facilitate technology diffusion is essential. They can take incremental steps and adjust the necessary levers to motivate, educate and obtain buy-in from employees. This ultimately brings companies to higher level of productivity.

- c. *Team coordination* ($\beta = 0.162$). Effective team coordination minimise conflicts and improve productivity between stakeholders across the PC supply chain. As illustrated in this study, to improve team coordination, existing key workflows and current practices need to be captured and documented, so that a well-coordinated workflow may be achieved for productivity improvement with the support of BIM cloud-enabled systems.
- d. *Information sharing* ($\beta = 0.132$). Information sharing enhance productivity by improving partnership among project stakeholders. This study has demonstrated that information technology can facilitate in information flow and bring about productivity improvement to key workflows in the pre- and post-production phases.

To demonstrate the usefulness of the PC-CSF performance analytical model and its factors in real-world scenarios. The four factors were applied collectively to improve the productivity of the key workflows in the PC supply chain.

7.2.2 Contributions to the industry

4. To demonstrate and validate these factors are useful for the PC manufacturer and its supply chain.

An established PC manufacturer was selected and three key workflows in the PC supply chain were identified as case studies. The four PC-CSF performance factors in the analytical model were collectively applied to the three case studies, namely (1) approval of shop drawing for production, (2) tracking and delivery of inventory and (3) progress claim and payment. To support the application of the factors, a purpose-built BIM cloud-enabled system called Production Logistic Management System (PLMS) was developed. It comprises three key modules (1) System for Shop Drawing Approval (SSDA), (2) System for Inventory Tracking and Delivery (SITD) with Proof of Delivery (POD), (3) System for Progress Claim and Payment (SPCP) to enhance the team coordination and information sharing of the respective key workflows. The results in chapter 6 have demonstrated the usefulness of the PC-CSF performance factors. The improvement in productivity of the three case studies are summarised in the next section.

5. To analyse and present the productivity improvement data across the identified key workflows in the PC supply chain.

To test the hypothesis H₉, the productivity gained of each case study is obtained by comparing the total duration (man-days per project) of the current-state key workflows and the newly developed key workflows.

- *Case 1: Approval of shop drawing for production.* By applying the PC-CSF performance factors with the support of the SSDA system, the total duration of the shop drawing approval workflow has been reduced from 68 man-days to approximately 43 man-days, giving a total 37% improvement in productivity. Furthermore, a 15% saving in manpower across the entire workflow has been achieved.
- *Case 2: Tracking and delivery of inventory.* Similarly, the application of the PC-CSF performance factors supported by the SITD system has drastically reduced the total duration of the tracking and delivery workflow from 94 man-days to 56 man-days, with 40% productivity improvement. With the implementation of the POD system, project stakeholders have full visibility of the PC panel delivery status, eliminating ambiguity and improved the quality-of-service of the PC manufacturers. In total, a reduction of 30% in manpower has been attained.
- *Case 3: Progress claim and payment.* The application of the PC-CSF performance factors supported by the SPCP system has improved the productivity of the progress claim and payment workflow. The total duration of the workflow has been reduced from 71 man-days to 19 man-days, with a total productivity improvement of 73%. In this workflow, a total of 57% reduction in manpower can be expected.

The field results from the productivity improvement of the three case studies have confirmed that the hypothesis H₉ “The combined benefits of the PC-CSF performance factors could greatly improve the productivity of key workflows in the PC supply chain” is supported.

7.3 Discussion and recommendations

A total of eight CSFs have been identified as critical success factors affecting BIM adoption. However, the regression model has suggested that only four factors contribute directly to productivity improvement.

1. Results have demonstrated that the productivity of key workflows in the PC supply chain can be improved by applying the four PC-CSF performance factors collectively. Clearly, the combination of the four factors, i.e., (a) constructible BIM, (b) top management commitment, (c) team coordination and (d) information sharing can bring about productivity improvement to the PC supply chain. It is worth noting that the purpose-built BIM-cloud systems have played a pivotal role, i.e., real-time team coordination and information sharing were made possible through the IFC data model hosted in the common data environment.
2. The regression analysis has suggested that (a) government policies, (b) competitive advantage, (c) drawing approval and (d) local support have no direct bearing on productivity improvement. The following explain:
 - a. *Government policies.* The government can establish the necessary guidelines, policies and incentive to help drive productivity, the rest is up to the industry. Many studies has acknowledged government as one of the key drivers in technology adoption. In general, the government plays a leading role in promoting the use of BIM technology. Taking Singapore as an example, its government, through BCA (www.bca.gov.sg), has been promoting the use of buildable design to increase site productivity. However, despite the years of government supports, productivity across the different sectors in the construction industry is still on a decline (BCA, 2020). In other words, while government may continue to support and fund initiatives to help spur technology adoption, the industry as well as the respective companies need to do their part by embracing changes and technology to reap the benefits (e.g., productivity gain) from government supports.
 - b. *Competitive advantage.* Using BIM can only be a competitive advantage when key workflows improve. Most of the respondents have recognised the potential of BIM to help them gain a competitive advantage among the market. With the increasing

use of precast components, subcontractors like PC manufacturers consequently play a critical role in the overall performance of the project. In order for the PC manufacturers to build confidence with their clients, that is, the general contractors, they need to be seen as active players in innovation, with expertise that will give them the competitive edge in a changing market (Lim, 2014). However, successful BIM adoption requires the alignment of work processes as well as the willingness to coordinate among the stakeholders (Mahalingam, Yadav, & Varaprasad, 2015). Unless management attitude and key workflows within the organisation and among the stakeholders improve, insufficient team coordination among companies will be a risk in technology adoption (e.g., BIM) and productivity (Fulford & Standing, 2014).

- c. *Drawing approval.* Significant research has taken place to discuss the factors of delay in the construction industry and slow shop drawing approval is frequently cited as a major issue (Atkins & Simpson, 2008; Faridi & El-Sayegh, 2006). PC manufacturers cannot commence production until the shop drawing is approved by the design team, impacting productivity. As demonstrated in this study, to achieve sustainable productivity improvement, there must be radical process change and enhancement of drawing approval workflow through the adoption of technology such as BIM. In other words, controlling the frequency of change orders alone will not help improve productivity, collaborative platform such as BIM cloud-enabled system must be considered.
- d. *Local support.* Implementing BIM is a very large undertaking and requires a great deal of planning. Companies will have to consider many aspects, such as (1) managing the resistance to change, (2) educating employees and developing BIM expertise, (3) preparing enough time for changes, (4) motivating and recognising employee's BIM efforts, and others (Bew & Underwood, 2010). As such, local support from BIM software vendors can greatly assist the companies in their BIM implementation and adoption process. However, if companies are not ready to do the abovementioned, the availability of vendor support will not be of value to their BIM adoption journey, let alone productivity improvement. This implies that any support from vendors is deemed irrelevant.

Based on the research results, there are several insightful managerial implications for the PC supply chain.

1. *Advocate a concerted approach to improve the overall productivity of the PC supply chain.* Construction supply chain is a collection of different project stakeholders coming together to deliver a project. This study has highlighted the importance of top management role in driving productivity improvement. Deliberate attempt must come from the top management to champion and encourage technology adoption that lead to productivity gain. In other words, to obtain a higher level of productivity in the PC supply chain, there must be collectively efforts to ensure the diffusion of technology to improve team coordination and information sharing within the organisation and among external project stakeholders.
2. *Information technology is pivotal to improving the PC supply chain productivity.* The basis of productivity improvement is the provision of information, usually by IT, across the supply chain. The prerequisite to productivity improvement in a supply chain is about integrating the different systems to tightly connect the respective project stakeholders. This study has demonstrated the transformative capabilities of BIM cloud-enabled system to improve the key workflows of the PC supply. It has certainly played a key role to improve team coordination and information sharing among project participants.
3. *Promote and facilitate a collaborative culture for productivity improvement in the construction industry.* The construction industry has been fragmented. Various companies come together to work on a project and when the project is completed, they disband and move on to the next project. Information and knowledge gathered during that period of work is hoarded instead of disseminated to other projects. This study has suggested that companies should turn away from their traditional project delivery practices and embrace information technology to manage team coordination and improve information sharing. A key part of this is to obtain an in-depth understanding of the current-state practices, and then apply the relevant IT (such as BIM and BIM cloud platform) to build a collaborative culture and yield sustainable productivity improvement in the supply chain.

7.4 Limitations and recommendations for future research

As with any research, this study has its limitations. The following are suggested for future research:

1. This research predominantly focusses on the precast BIM adoption status in Singapore. In Singapore, there are a total of 50 companies registered as “CR10 – Precast concrete works” contractors (BCA directory, 2018) during the time of the survey. Future studies should reach out to more PC companies across the region to obtain a wider and more diverse perspective on BIM adoption and factors that lead to productivity improvement.
2. The case studies were limited to the set of data provided by one PC manufacturer and main contractor during the case study. According to Yin (2014), the case studies lead to “analytic generalisation”, i.e., generalisable to theoretical proposition and not the populations. In other words, future studies are needed to focus on applying the PC-CSF performance analytical model to similar populations and expect similar findings.
3. This study was conducted based on the perspective of the PC manufacturer. The key workflows and data collected were from the viewpoint of the subject-matter-experts of the selected PC manufacturer. As such, future studies should also include the perspective of other key players in the PC supply chain, such as the main contractors, consultants and project owners. This will enable the researcher to obtain a global view of the PC supply chain, so that relevant solutions can also be developed to address the specific needs for the rest of the project stakeholders.
4. The current industry practice is to communicate by means of 2D drawings among stakeholders. However, it will be much more efficient to collaborate with BIM at the start of the project. To realise the full potential of BIM, the whole ecosystem needs to embrace it, and not just merely the responsibility of a single party. For instance, the approval of shop drawing workflow can be further streamlined by leveraging the benefits derived from BIM model. Further research can explore the possibility of full BIM deployment in the supply chain, when the industry is more ready to embrace IT.

5. This research focused on workflows of panelised system (i.e., two-dimensional). It does not cover modular or volumetric system (i.e., three-dimensional) such as Prefabricated Prefinished Volumetric Construction (PPVC). With the even increased interest in modular system, the PC-CSF performance analytical model can be adopted to optimise the PPVC supply chain workflows. Future studies can focus on implementing the model and its complementary BIM cloud-enabled system to bring about an improvement of productivity.

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Appendix A List of papers from systematic analysis

The 64 articles that fall under the scope of precast in civil engineering, building management and construction are listed below.

Authors	Title	Research theme	Keywords
An et al. (2020)	BIM-based decision support system for automated manufacturability check of wood frame assemblies	BIM-based framework for automating the evaluation of machine capabilities for the manufacturing of construction-oriented products.	BIM and information technology
Nekouvaght et al. (2020)	Evaluating industrial modularization strategies: Local vs. overseas fabrication	An integrated framework to evaluate different module fabrication strategies.	Construction project management
Guo et al. (2020)	Geometric quality inspection of prefabricated MEP modules with 3D laser scanning	Automated geometric quality inspection technique to estimate the geometric properties of MEP modules using 3D laser scanning.	BIM and information technology
Khalili-Araghi and Kolarevic (2020)	Variability and validity: Flexibility of a dimensional customization system	Automatic design validation in the housing industry.	Precast concrete design
Charef et al. (2019)	Building Information Modelling adoption in the European Union: An overview	Twenty barriers to BIM adoption in the Architecture, Engineering, Construction and Operation (AECO) industry.	BIM Adoption/implementation
Chan et al. (2019)	Perceived benefits of and barriers to Building Information Modelling (BIM) implementation in construction: The case of Hong Kong	The perceived benefits of and barriers to BIM implementation in the Hong Kong construction industry.	BIM Adoption/implementation
Babatunde and Ekundayo (2019)	Barriers to the incorporation of BIM into quantity surveying undergraduate curriculum in the Nigerian universities	The barriers to the incorporation of BIM into quantity surveying (QS) undergraduate curriculum in Nigerian universities.	Education and training
Yu et al. (2019)	Prioritization of BIM Uses - A Case Study Of Taiwan BIM Guide [BIM 應用選擇優先性分析－以台灣 BIM 指南為例]	A useful adoption guideline for the BIM project owners.	BIM Adoption/implementation
Roslan et al. (2019)	Building information modelling (BIM) stage 2 implementation strategy for the construction industry in Malaysia	The status of BIM adoption in Malaysia.	BIM Adoption/implementation
Enshassi et al. (2019)	Limitation factors of building information modeling (BIM) Implementation	Factors that limit BIM implementation in the construction industry.	BIM Adoption/implementation
Moreno et al. (2019)	BIM Use by Architecture, Engineering, and Construction (AEC) Industry in Educational Facility Projects	BIM use on educational facility projects resulting in better quality educational buildings.	Education and training

Ismail (2019)	An Integrated Computerised Maintenance Management System (I-CMMS) for IBS building maintenance	An integrated computerised maintenance management system for IBS building through the integration of BIM.	BIM and information technology
Lee et al. (2019)	The Mechanism and Challenges of Validating a Building Information Model regarding data exchange standards	BIM data validation using the MVD relating to procedures, scope, and complexity.	BIM and information technology
Ma et al. (2019)	Visualization of Component Status Information of Prefabricated Concrete Building Based on Building Information Modeling and Radio Frequency Identification: A Case Study in China	Building information modelling (BIM) and radio frequency identification (RFID) technologies to visualize the state information of prefabricated concrete components.	BIM and information technology
Lee et al. (2019)	BIM-Based Digital Fabrication Process for a Free-Form Building Project in South Korea	BIM-based digital fabrication process for prefabricated parts of buildings.	BIM and information technology
Zhao et al. (2019)	Optimization of the supplier selection process in prefabrication using BIM	A method for supporting supplier selection of a prefabrication project.	Construction project management
Bortolini et al. (2019)	Site logistics planning and control for engineer-to-order prefabricated building systems using BIM 4D modeling	Logistics planning and control model for site assembly of ETO prefabricated building systems using BIM 4D modelling.	Construction project management
Boon et al. (2019)	Building information modelling integrated project delivery system in Malaysia	The principles of IPD in Malaysia followed by examining the implementation level of IPD in Malaysian construction industry as well as evaluate the BIM integration in Integration Project Delivery.	Construction project management
Zhang and Dong (2019)	Application Study on Building Information Model (BIM) Standardization of Chinese Engineering Breakdown Structure (EBS) Coding in Life Cycle Management Processes	An EBS standard that embodies a coding system for highways and the requirements of BIM management, project management (PM), and operation management (OM) in life cycle management process.	Design and Standards
Gamil and Rahman (2019)	Awareness and challenges of building information modelling (BIM) implementation in the Yemen construction industry	The awareness and challenges of implementing BIM in the Yemen construction industry.	BIM Adoption/ implementation
Ahmed and Kassem (2018)	A unified BIM adoption taxonomy: Conceptual development, empirical validation and application	A Unified BIM Adoption Taxonomy (UBAT); and to identify the taxonomy's constructs.	BIM Adoption/ implementation
Arunkumar et al. (2018)	A feasibility study on the implementation of building information modeling (BIM): from the architects' & engineers' perspective	The attitude of the professionals in AEC industry regarding the positive and negative factors influencing the implementation of BIM in the AEC industry.	BIM Adoption/ implementation
Addy M et al. (2018)	Antecedents of building information modelling adoption among quantity surveyors in Ghana: An application of a technology acceptance model	The factors that facilitate adoption of building information modelling (BIM) among quantity surveyors (Qs) using the unified theory of acceptance and use of technology (UTAUT).	BIM Adoption/ implementation

Teng et al. (2018)	Current BIM practices in Malaysian construction organisations: The stakeholders' perspective	The benefits and barriers that could be encountered in BIM implementation from the construction stakeholders' perspectives.	BIM Adoption/implementation
Samad et al. (2018)	The potential use of BIM through an electronic submission: A preliminary study	The potential of BIM implementation within the public sector, specifically how BIM could be utilised to facilitate electronic submission.	BIM and information technology
Li et al. (2018)	An Internet of Things-enabled BIM platform for on-site assembly services in prefabricated construction	An Internet of Things (IoT)-enabled platform is designed by integrating IoT and BIM for prefabricated public housing projects in Hong Kong.	BIM and information technology
Hernández et al. (2018)	An IFC interoperability framework for self-inspection process in buildings	A framework under which the equipment to improve interoperability between the various equipment used to carry out self-inspection.	BIM and information technology
Jang and Lee (2018)	Process, productivity, and economic analyses of BIM-based multi-trade prefabrication—A case study	The productivity, and economic benefits of BIM-based MTP through a case study.	Construction project management
Zhang et al. (2018)	Design and building method for fabricated light-wood frame structures by building information modeling [基于建筑信息建模的装配式轻型木结构设计建造方法]	A proposed design and building method can improve the precision of prefabrication and assembly.	Design and Standards
Yuan et al. (2018)	Design for Manufacture and Assembly-oriented parametric design of prefabricated buildings	Introducing Design for Manufacture and Assembly (DFMA) into prefabricated building design	Design and Standards
Li et al. (2017)	Barriers to building information modelling in the Chinese construction industry	The barriers in BIM implementation of owners, designers and contractors.	BIM Adoption/implementation
Abanda et al. (2017)	BIM in off-site manufacturing for buildings	The implications of BIM systems on off-site manufacture.	BIM and information technology
Zhong et al. (2017)	Prefabricated construction enabled by the Internet-of-Things	The Internet of Things (IoT)-enabled BIM platform (MITBIMP) to achieve real-time visibility and traceability in prefabricated construction.	BIM and information technology
Hanafi et al. (2016)	Organisational readiness of building information modelling implementation: Architectural practices	The awareness of BIM implementation towards enhancing the efficiency and productivity of architecture firms.	BIM Adoption/implementation
Enegbuma et al. (2016)	Confirmatory strategic information technology implementation for building information modelling adoption model	The business process re-engineering and computer integrated construction for a BIM adoption model for architects, quantity surveyors, engineers and contractors.	BIM Adoption/implementation
Lee et al. (2016)	Modularized rule-based validation of a BIM model pertaining to model views	A robust MVD validation process using a modularized validation platform that evaluates an IFC instance file according to diverse types of rule sets of MVDs.	BIM and information technology
Kim et al. (2016)	Automated dimensional quality assurance of full-scale precast concrete elements using laser scanning and BIM	Quality inspection technique for full-scale precast concrete elements using laser scanning and building information modelling (BIM).	BIM and information technology

Abedi et al. (2016)	Integrated collaborative tools for precast supply chain management	The system architecture and prototype of Context-Aware Cloud Computing Building Information Modelling (CACCBIM) for precast supply chain management.	Construction project management
Wang et al. (2016)	Automated quality assessment of precast concrete elements with geometry irregularities using terrestrial laser scanning	An automated quality assessment technique which estimates the dimensions of precast concrete elements with geometry irregularities using terrestrial laser scanners (TLS).	BIM and information technology
Succar and Kassem (2015)	Macro-BIM adoption: Conceptual structures	BIM adoption across markets and inform the structured development of country-specific BIM adoption policies.	BIM Adoption/implementation
Son et al. (2015)	What drives the adoption of building information modeling in design organizations? An empirical investigation of the antecedents affecting architects' behavioral intentions	The factors that can potentially facilitate architects' adoption of BIM through an extension of the technology acceptance model.	BIM Adoption/implementation
Nath et al. (2015)	Productivity improvement of precast shop drawings generation through BIM-based process re-engineering	The constraints in the present workflow for precast shop drawing generation and to propose a BIM-based enhanced workflow.	BIM and information technology
Kim et al. (2015)	A framework for dimensional and surface quality assessment of precast concrete elements using BIM and 3D laser scanning	An end-to-end framework for dimensional and surface quality assessment of precast concrete elements based on BIM and 3D laser scanning.	Design and Standards
Liu et al. (2015)	BIM-based integrated approach for detailed construction scheduling under resource constraints	A BIM-based integrated scheduling approach which facilitates the automatic generation of optimized activity-level construction schedules.	BIM and information technology
Gilkinson et al. (2015)	Building information modelling: The tide is turning	Several case study research projects and discusses how this innovative solution works in practice in AEC industry.	BIM Adoption/implementation
Poirier et al. (2015)	Measuring the impact of BIM on labor productivity in a small specialty contracting enterprise through action-research	The impact of BIM on labour productivity on a large commercial project.	Construction project management
Cavka et al. (2015)	Evaluating the alignment of organizational and project contexts for BIM adoption: A case study of a large owner organization	The current organizational facility management (FM) practices and challenges of transitioning to a model-based approach.	Construction project management
Lee et al. (2015)	Validations for ensuring the interoperability of data exchange of a building information model	The development of solid frameworks for validating a building design.	Design and Standards
Tsai et al. (2014)	Developing critical success factors for the assessment of BIM technology adoption: Part I. Methodology and survey	Developing critical success factors (CSFs) that can be further developed for assessment of BIM adoption at organizational level in Taiwan's AEC industry.	BIM Adoption/implementation

Chien et al. (2014)	Identifying and assessing critical risk factors for BIM projects: Empirical study	Identified the critical risk factors of BIM projects at various levels and proposes relative risk-response strategies for a case study project.	Construction project management
Wong and Kuan (2014)	Implementing 'BEAM Plus' for BIM-based sustainability analysis	Explore the potential use of BIM in the case of a residential building project seeking BEAM Plus sustainable building certification in Hong Kong.	BIM and information technology
Liu et al. (2014)	Research and application of prefabricated and assembled residential building project information management platform based on BIM technology	The information management platform provides technology foundation for updating design and information retrieval at operation stage.	BIM and information technology
Moya and Pons (2014)	Improving the design and production data flow of a complex curvilinear geometric Glass Reinforced Concrete façade	Simplify the design and document development processes for curvilinear façades.	Design and Standards
Eadie et al. (2013)	BIM implementation throughout the UK construction project lifecycle: An analysis	Demonstrate that the process aspects are more important than the software technology by Facilities Managers.	BIM Adoption/ implementation
Porwal and Hewage (2013)	Building Information Modeling (BIM) partnering framework for public construction projects	A 'BIM partnering' based public procurement framework to ensure 'best value' in construction projects in the Canadian construction industry.	BIM and information technology
Davies and Harty (2013)	Implementing 'site BIM': A case study of ICT innovation on a large hospital project	BIM-enabled tools to allow site workers access design information and to capture work quality and progress data.	BIM and information technology
Larsen et al. (2011)	Surveying and digital workflow in energy performance retrofit projects using prefabricated elements	The approach for the surveying and documentation of a building's existing state and the need to establish a continuous digital chain.	BIM and information technology
Singh et al. (2011)	A theoretical framework of a BIM-based multi-disciplinary collaboration platform	A theoretical framework of technical requirements for using BIM-server as a multi-disciplinary collaboration platform.	BIM and information technology
Arayici et al. (2011)	BIM adoption and implementation for architectural practices	A systematic approach for building information modelling (BIM) implementation for architectural SMEs at the organizational level, incorporated people, process and technology.	Construction project management
Sacks et al. (2010a)	The Rosewood experiment - Building information modeling and interoperability for architectural precast facades	Building information modelling (BIM) and product data exchange in the design and fabrication of architectural precast façades.	BIM and information technology
Sacks et al. (2010b)	Requirements for building information modeling based lean production management systems for construction	Improve work flow and reduce waste by providing both process and product visualization at the work face.	BIM and information technology
Jeong et al. (2009)	Benchmark tests for BIM data exchanges of precast concrete	Data exchanges to achieve fully effective interoperability, a need for a mutually agreed upon standard.	Design and Standards
Lee et al. (2006)	Specifying parametric building object behavior (BOB) for a building information modeling system	Design and engineering knowledge to practically embedded in production software for building information modelling (BIM).	Design and Standards

Appendix B Raw data from questionnaire survey

The survey results are tabulated below.

	Government and market Forces				
No.	A1 Government policies and support on BIM implementation in precast sector	A2 Pressure from other Precast companies	A3 Demand from the ecosystem to use BIM for better collaborations i.e. Clients request for BIM	A4 Enhance company reputation through the use of new technologies like BIM	A5 BIM to be used as a competitive advantage
1	Important	Important	Important	Important	Very Important
2	Very Important	Important	Very Important	Important	Important
3	Important	Neutral	Important	Important	Important
4	Very Important	Very Important	Very Important	Very Important	Very Important
5	Very Important	Very Important	Very Important	Very Important	Very Important
6	Important	Important	Important	Very Important	Very Important
7	Very Important	Important	Very Important	Important	Very Important
8	Neutral	Neutral	Important	Important	Important
9	Very Important	Very Important	Very Important	Very Important	Very Important
10	Important	Neutral	Important	Important	Important
11	Very Important	Important	Very Important	Very Important	Very Important
12	Important	Neutral	Important	Important	Important
13	Very Important	Important	Important	Very Important	Very Important
14	Important	Important	Important	Important	Important
15	Important	Important	Important	Neutral	Important
16	Important	Important	Neutral	Important	Important
17	Very Important	Very Important	Very Important	Very Important	Very Important
18	Important	Neutral	Important	Neutral	Important
19	Very Important	Important	Important	Important	Important
20	Important	Neutral	Important	Important	Important
21	Important	Somewhat Important	Somewhat Important	Very Important	Important
22	Neutral	Very Important	Important	Important	Important
23	Very Important	Important	Important	Very Important	Very Important
24	Very Important	Neutral	Very Important	Very Important	Very Important
25	Important	Neutral	Neutral	Important	Important
26	Very Important	Neutral	Very Important	Important	Important
27	Very Important	Important	Important	Important	Very Important
28	Very Important	Neutral	Very Important	Neutral	Very Important
29	Very Important	Neutral	Very Important	Very Important	Very Important
30	Very Important	Important	Important	Very Important	Very Important
31	Very Important	Neutral	Neutral	Neutral	Neutral
32	Very Important	Important	Very Important	Important	Very Important
33	Neutral	Important	Somewhat Important	Somewhat Important	Important
34	Somewhat Important	Neutral	Very Important	Somewhat Important	Very Important
35	Very Important	Neutral	Very Important	Important	Important
36	Important	Important	Important	Important	Important
37	Very Important	Important	Important	Important	Important
38	Very Important	Very Important	Important	Important	Important
39	Very Important	Very Important	Very Important	Very Important	Very Important
40	Very Important	Neutral	Very Important	Important	Important
41	Neutral	Somewhat Important	Important	Very Important	Very Important

42	Very Important	Very Important	Very Important	Very Important	Very Important
43	Neutral	Neutral	Very Important	Very Important	Very Important
44	Neutral	Neutral	Neutral	Very Important	Very Important
45	Very Important	Very Important	Very Important	Very Important	Very Important
46	Very Important	Very Important	Very Important	Very Important	Very Important
47	Important	Neutral	Important	Very Important	Very Important
48	Important	Important	Important	Important	Important
49	Very Important	Neutral	Neutral	Important	Important
50	Very Important	Very Important	Neutral	Very Important	Very Important
51	Very Important	Neutral	Very Important	Important	Very Important
52	Very Important	Important	Very Important	Very Important	Very Important
53	Neutral	Important	Neutral	Neutral	Somewhat Important

Company					
No.	B1	B2	B3	B4	B5
	Persistent commitment of top management on BIM adoption	BIM training roadmap to build BIM capabilities at different level (i.e. from management of BIM users)	Company willingness to change of workflows	Setting up a BIM committee to help steer BIM implementation in the company	Dedicated BIM department/ team that supports all BIM requests
1	Important	Very Important	Important	Important	Very Important
2	Very Important	Very Important	Important	Important	Very Important
3	Important	Important	Important	Important	Important
4	Very Important	Important	Important	Important	Important
5	Very Important	Very Important	Very Important	Very Important	Very Important
6	Very Important	Important	Neutral	Important	Very Important
7	Very Important	Important	Important	Neutral	Neutral
8	Important	Very Important	Very Important	Neutral	Very Important
9	Very Important	Important	Very Important	Important	Very Important
10	Important	Important	Important	Neutral	Neutral
11	Very Important	Very Important	Very Important	Very Important	Very Important
12	Important	Important	Important	Important	Important
13	Very Important	Important	Important	Important	Very Important
14	Important	Important	Important	Important	Important
15	Important	Important	Important	Neutral	Neutral
16	Important	Neutral	Important	Very Important	Important
17	Very Important	Very Important	Very Important	Very Important	Very Important
18	Important	Important	Important	Important	Important
19	Neutral	Neutral	Neutral	Neutral	Neutral
20	Important	Important	Important	Important	Important
21	Important	Important	Important	Important	Important
22	Important	Important	Very Important	Important	Important
23	Very Important	Important	Important	Not Important	Somewhat Important
24	Very Important	Very Important	Very Important	Very Important	Very Important
25	Important	Important	Important	Neutral	Important
26	Very Important	Very Important	Very Important	Very Important	Very Important
27	Very Important	Important	Important	Important	Important
28	Neutral	Neutral	Neutral	Neutral	Neutral
29	Very Important	Very Important	Very Important	Very Important	Very Important

30	Very Important	Very Important	Very Important	Neutral	Important
31	Important	Important	Very Important	Important	Very Important
32	Very Important	Very Important	Very Important	Very Important	Very Important
33	Important	Very Important	Very Important	Neutral	Important
34	Very Important	Very Important	Very Important	Important	Very Important
35	Very Important	Important	Important	Important	Important
36	Important	Important	Important	Important	Important
37	Important	Important	Important	Important	Important
38	Very Important	Important	Important	Very Important	Important
39	Very Important	Very Important	Very Important	Important	Very Important
40	Very Important	Important	Important	Important	Very Important
41	Important	Very Important	Neutral	Important	Important
42	Very Important	Very Important	Very Important	Very Important	Very Important
43	Very Important	Very Important	Very Important	Neutral	Very Important
44	Very Important	Very Important	Very Important	Very Important	Very Important
45	Very Important	Very Important	Very Important	Very Important	Very Important
46	Important	Important	Important	Important	Very Important
47	Important	Important	Very Important	Very Important	Very Important
48	Very Important	Important	Very Important	Important	Very Important
49	Important	Important	Important	Important	Important
50	Very Important	Very Important	Very Important	Very Important	Very Important
51	Very Important	Very Important	Very Important	Important	Very Important
52	Very Important	Very Important	Very Important	Very Important	Very Important
53	Not Important	Not Important	Not Important	Not Important	Not Important

	Team				
	C1	C2	C3	C4	C5
No.	Finding employees with BIM modelling skill set	Getting people to understand the potential and value of BIM over 2D drafting	Give adequate time and bandwidth to the team members, during the transition phase to BIM	Early involvement of team members to build strategies for change i.e. Get early buy-in of team.	Certification in BIM for Precast to assess individual understanding of BIM.
1	Very Important	Very Important	Important	Important	Very Important
2	Very Important	Important	Important	Neutral	Important
3	Important	Important	Important	Important	Important
4	Important	Very Important	Neutral	Neutral	Very Important
5	Neutral	Very Important	Important	Neutral	Very Important
6	Very Important	Important	Important	Neutral	Neutral
7	Important	Not Important	Somewhat Important	Neutral	Neutral
8	Important	Very Important	Very Important	Very Important	Very Important
9	Very Important	Very Important	Very Important	Very Important	Very Important
10	Very Important	Neutral	Important	Important	Neutral
11	Very Important	Important	Very Important	Neutral	Important
12	Important	Important	Important	Important	Neutral
13	Important	Important	Neutral	Important	Very Important
14	Important	Important	Important	Important	Important

15	Important	Important	Important	Neutral	Neutral
16	Important	Important	Very Important	Important	Important
17	Very Important	Very Important	Very Important	Very Important	Very Important
18	Important	Important	Important	Important	Important
19	Important	Important	Very Important	Neutral	Neutral
20	Important	Important	Important	Important	Important
21	Important	Important	Very Important	Important	Neutral
22	Important	Important	Important	Very Important	Neutral
23	Important	Somewhat Important	Not Important	Not Important	Very Important
24	Very Important	Very Important	Very Important	Very Important	Very Important
25	Important	Important	Neutral	Neutral	Important
26	Important	Neutral	Very Important	Very Important	Important
27	Important	Very Important	Very Important	Very Important	Important
28	Neutral	Neutral	Neutral	Neutral	Neutral
29	Neutral	Very Important	Neutral	Very Important	Neutral
30	Very Important	Very Important	Very Important	Important	Very Important
31	Very Important	Very Important	Important	Very Important	Neutral
32	Neutral	Very Important	Important	Important	Neutral
33	Very Important	Important	Very Important	Important	Neutral
34	Very Important	Very Important	Very Important	Very Important	Neutral
35	Very Important	Important	Important	Important	Important
36	Important	Important	Important	Important	Important
37	Important	Important	Important	Important	Important
38	Important	Very Important	Very Important	Important	Neutral
39	Very Important	Very Important	Very Important	Important	Important
40	Important	Important	Important	Very Important	Important
41	Neutral	Not Important	Somewhat Important	Neutral	Important
42	Very Important	Very Important	Very Important	Very Important	Very Important
43	Very Important	Very Important	Very Important	Very Important	Very Important
44	Very Important	Very Important	Very Important	Very Important	Very Important
45	Very Important	Very Important	Very Important	Important	Important
46	Neutral	Important	Somewhat Important	Neutral	Important
47	Important	Very Important	Very Important	Important	Important
48	Important	Important	Important	Important	Neutral
49	Important	Important	Important	Important	Neutral
50	Important	Important	Very Important	Important	Neutral
51	Very Important	Very Important	Very Important	Important	Important
52	Very Important	Very Important	Very Important	Very Important	Very Important
53	Somewhat Important	Neutral	Not Important	Not Important	Somewhat Important

	Process				
	D1	D2	D3	D4	D5
No.	In a typical project, the precast design intent is discussed at	BIM models provided by structural	Data extracted from the BIM models	BIM models interface with Enterprise	Drawing production can be faster if

	the initial design stage, including design of precast structures and precast connections	engineers contain sufficient and accurate information. (i.e. for further processing)	improves productivity.	Resource Planning (ERP) system.	changes are well controlled, and hence shorten production time.
1	Strongly agree	Strongly agree	Strongly agree	Strongly agree	Strongly agree
2	Disagree	Neither agree nor disagree	Strongly agree	Neither agree nor disagree	Neither agree nor disagree
3	Strongly agree	Strongly disagree	Agree	Strongly agree	Strongly agree
4	Agree	Neither agree nor disagree	Agree	Agree	Strongly agree
5	Agree	Strongly agree	Strongly agree	Strongly agree	Strongly agree
6	Strongly agree	Neither agree nor disagree	Agree	Agree	Strongly agree
7	Disagree	Neither agree nor disagree	Disagree	Neither agree nor disagree	Strongly agree
8	Strongly agree	Neither agree nor disagree	Strongly agree	Strongly agree	Strongly agree
9	Strongly agree	Strongly agree	Strongly agree	Strongly agree	Strongly agree
10	Agree	Agree	Agree	Neither agree nor disagree	Agree
11	Strongly agree	Strongly agree	Agree	Agree	Agree
12	Agree	Agree	Agree	Neither agree nor disagree	Agree
13	Strongly agree	Agree	Strongly agree	Neither agree nor disagree	Agree
14	Neither agree nor disagree	Neither agree nor disagree	Neither agree nor disagree	Neither agree nor disagree	Agree
15	Agree	Agree	Agree	Agree	Agree
16	Neither agree nor disagree	Agree	Agree	Agree	Agree
17	Strongly agree	Neither agree nor disagree	Strongly agree	Neither agree nor disagree	Strongly agree
18	Strongly agree	Strongly agree	Strongly agree	Strongly agree	Strongly agree
19	Strongly agree	Strongly agree	Agree	Agree	Agree
20	Agree	Neither agree nor disagree	Agree	Agree	Agree
21	Agree	Agree	Neither agree nor disagree	Neither agree nor disagree	Agree
22	Agree	Agree	Agree	Agree	Strongly agree
23	Neither agree nor disagree	Strongly agree	Strongly agree	Strongly agree	Strongly agree
24	Strongly agree	Disagree	Agree	Strongly agree	Strongly agree
25	Agree	Neither agree nor disagree	Agree	Agree	Agree
26	Strongly agree	Neither agree nor disagree	Strongly agree	Agree	Strongly agree
27	Strongly agree	Agree	Strongly agree	Agree	Strongly agree
28	Strongly agree	Strongly agree	Strongly agree	Strongly agree	Strongly agree
29	Strongly agree	Strongly agree	Neither agree nor disagree	Strongly agree	Strongly agree
30	Neither agree nor disagree	Strongly disagree	Strongly agree	Strongly agree	Strongly agree
31	Neither agree nor disagree	Disagree	Strongly agree	Strongly agree	Strongly agree
32	Strongly agree	Strongly agree	Agree	Strongly agree	Agree

33	Neither agree nor disagree	Disagree	Disagree	Neither agree nor disagree	Disagree
34	Disagree	Agree	Neither agree nor disagree	Agree	Strongly agree
35	Agree	Neither agree nor disagree	Agree	Agree	Agree
36	Agree	Agree	Strongly agree	Agree	Strongly agree
37	Agree	Neither agree nor disagree	Strongly agree	Agree	Agree
38	Agree	Agree	Agree	Strongly agree	Neither agree nor disagree
39	Strongly agree	Disagree	Agree	Neither agree nor disagree	Strongly agree
40	Agree	Agree	Neither agree nor disagree	Neither agree nor disagree	Agree
41	Agree	Agree	Disagree	Agree	Agree
42	Strongly agree	Strongly agree	Strongly agree	Strongly agree	Strongly agree
43	Strongly agree	Strongly agree	Strongly agree	Strongly agree	Strongly agree
44	Strongly agree	Strongly agree	Neither agree nor disagree	Strongly agree	Strongly agree
45	Agree	Disagree	Neither agree nor disagree	Neither agree nor disagree	Strongly agree
46	Neither agree nor disagree	Disagree	Agree	Agree	Neither agree nor disagree
47	Neither agree nor disagree	Neither agree nor disagree	Agree	Neither agree nor disagree	Strongly agree
48	Agree	Neither agree nor disagree	Neither agree nor disagree	Agree	Agree
49	Strongly agree	Neither agree nor disagree	Neither agree nor disagree	Neither agree nor disagree	Strongly agree
50	Agree	Agree	Agree	Strongly agree	Strongly agree
51	Strongly agree	Disagree	Strongly agree	Agree	Strongly agree
52	Strongly agree	Strongly agree	Strongly agree	Strongly agree	Strongly agree
53	Strongly disagree	Disagree	Neither agree nor disagree	Disagree	Disagree

BIM Software Tool					
No.	E1	E2	E3	E4	E5
	The simplicity (ease of modelling with libraries support) of use.	The interoperability of the BIM software with other applications and machinery.	The customisability of the BIM software to address the requirements of every Precast companies.	The reputation of BIM software (i.e. well known for successful engagement with Precast companies.)	The availability of local support team. BIM software vendors' timely technical support.
1	Important	Very Important	Important	Very Important	Very Important
2	Important	Important	Very Important	Very Important	Important
3	Important	Very Important	Very Important	Very Important	Very Important
4	Very Important	Very Important	Very Important	Very Important	Very Important
5	Very Important	Very Important	Very Important	Very Important	Very Important
6	Important	Very Important	Important	Neutral	Important
7	Very Important	Very Important	Very Important	Neutral	Very Important
8	Very Important	Very Important	Very Important	Very Important	Very Important
9	Very Important	Very Important	Very Important	Very Important	Very Important
10	Neutral	Neutral	Neutral	Neutral	Neutral
11	Very Important	Very Important	Very Important	Very Important	Very Important
12	Important	Important	Important	Important	Important
13	Important	Important	Important	Important	Very Important

14	Important	Important	Important	Important	Important
15	Important	Important	Neutral	Important	Neutral
16	Very Important	Important	Important	Important	Very Important
17	Very Important	Very Important	Very Important	Very Important	Very Important
18	Very Important	Very Important	Important	Important	Very Important
19	Important	Important	Important	Important	Important
20	Very Important	Very Important	Very Important	Very Important	Very Important
21	Important	Important	Important	Important	Important
22	Important	Very Important	Very Important	Important	Very Important
23	Very Important	Very Important	Very Important	Important	Very Important
24	Very Important	Very Important	Very Important	Very Important	Very Important
25	Neutral	Important	Important	Important	Important
26	Very Important	Very Important	Important	Very Important	Very Important
27	Very Important	Important	Very Important	Important	Very Important
28	Very Important	Very Important	Very Important	Very Important	Very Important
29	Very Important	Very Important	Very Important	Important	Very Important
30	Very Important	Very Important	Very Important	Important	Very Important
31	Very Important	Very Important	Very Important	Important	Very Important
32	Very Important	Very Important	Very Important	Important	Very Important
33	Very Important	Very Important	Important	Neutral	Very Important
34	Very Important	Very Important	Very Important	Important	Neutral
35	Important	Important	Important	Important	Important
36	Important	Important	Important	Important	Very Important
37	Important	Important	Important	Important	Important
38	Very Important	Very Important	Very Important	Important	Very Important
39	Very Important	Very Important	Important	Important	Very Important
40	Important	Important	Important	Important	Important
41	Important	Neutral	Important	Important	Important
42	Very Important	Very Important	Very Important	Very Important	Very Important
43	Neutral	Neutral	Neutral	Very Important	Very Important
44	Very Important	Very Important	Very Important	Very Important	Very Important
45	Very Important	Important	Very Important	Important	Very Important
46	Neutral	Neutral	Neutral	Important	Very Important
47	Important	Very Important	Important	Important	Very Important
48	Important	Important	Very Important	Important	Important
49	Important	Very Important	Important	Important	Important
50	Very Important	Very Important	Important	Important	Very Important
51	Very Important	Very Important	Important	Very Important	Very Important
52	Very Important	Very Important	Very Important	Very Important	Very Important
53	Somewhat Important	Neutral	Neutral	Neutral	Not Important

BIM utilisation and expectation of PC manufacturers				
No.	PC1 The company uses BIM models to extract bill of quantities for material purchasing and tendering	PC2 The company uses BIM for productivity improvement	PC3 The company uses BIM models to convey design intent, enhance communication and coordination among stakeholders	PC4 The company does not use BIM
1	Strongly agree	Strongly agree	Strongly agree	Neither agree nor disagree
2	Agree	Agree	Neither agree nor disagree	Disagree
3	Agree	Strongly agree	Agree	Strongly disagree
4	Agree	Agree	Agree	Disagree
5	Strongly agree	Strongly agree	Strongly agree	Neither agree nor disagree
6	Agree	Strongly agree	Agree	Neither agree nor disagree
7	Agree	Agree	Agree	Strongly disagree

8	Agree	Agree	Agree	Strongly disagree
9	Strongly agree	Strongly agree	Strongly agree	Neither agree nor disagree
10	Agree	Neither agree nor disagree	Agree	Strongly disagree
11	Strongly agree	Strongly agree	Strongly agree	Neither agree nor disagree
12	Agree	Agree	Agree	Disagree
13	Agree	Strongly agree	Agree	Strongly disagree
14	Agree	Agree	Agree	Strongly disagree
15	Agree	Agree	Agree	Disagree
16	Agree	Agree	Agree	Neither agree nor disagree
17	Strongly agree	Strongly agree	Strongly agree	Strongly disagree
18	Agree	Strongly agree	Agree	Neither agree nor disagree
19	Agree	Agree	Strong agree	Neither agree nor disagree
20	Agree	Agree	Agree	Disagree
21	Agree	Agree	Neither agree nor disagree	Strongly agree
22	Agree	Agree	Neither agree nor disagree	Neither agree nor disagree
23	Strongly agree	Strongly agree	Agree	Strongly disagree
24	Strongly agree	Strongly agree	Strongly agree	Neither agree nor disagree
25	Agree	Agree	Neither agree nor disagree	Disagree
26	Agree	Strongly agree	Strongly agree	Neither agree nor disagree
27	Strongly agree	Strongly agree	Strongly agree	Neither agree nor disagree
28	Agree	Strongly agree	Strongly agree	Strongly agree
29	Strongly agree	Strongly agree	Strongly agree	Neither agree nor disagree
30	Agree	Agree	Agree	Neither agree nor disagree
31	Neither agree nor disagree	Agree	Neither agree nor disagree	Neither agree nor disagree
32	Strongly agree	Strongly agree	Strongly agree	Strongly disagree
33	Neither agree nor disagree	Neither agree nor disagree	Agree	Strongly agree
34	Agree	Agree	Agree	Strongly disagree
35	Agree	Agree	Agree	Neither agree nor disagree
36	Agree	Agree	Agree	Disagree
37	Agree	Agree	Agree	Disagree
38	Agree	Strongly agree	Strongly agree	Neither agree nor disagree
39	Agree	Agree	Neither agree nor disagree	Strongly agree
40	Agree	Agree	Agree	Neither agree nor disagree
41	Agree	Agree	Neither agree nor disagree	Neither agree nor disagree
42	Strongly agree	Strongly agree	Strongly agree	Neither agree nor disagree
43	Strongly agree	Strongly agree	Agree	Disagree
44	Strongly agree	Strongly agree	Strongly agree	Strongly disagree
45	Agree	Neither agree nor disagree	Neither agree nor disagree	Neither agree nor disagree
46	Neither agree nor disagree	Agree	Neither agree nor disagree	Neither agree nor disagree
47	Agree	Agree	Neither agree nor disagree	Disagree

48	Agree	Strongly agree	Agree	Neither agree nor disagree
49	Agree	Agree	Agree	Disagree
50	Agree	Strongly agree	Agree	Neither agree nor disagree
51	Agree	Agree	Neither agree nor disagree	Agree
52	Strongly agree	Strongly agree	Strongly agree	Neither agree nor disagree
53	Disagree	Disagree	Disagree	Strongly agree

Appendix C The companies' BIM maturity statuses and BIM adopter's model

The BIM maturity statuses

The companies' BIM maturity statuses were obtained from the following table which is derived based on JRC Technical Report – Building Information Modelling (BIM) Standardisation to collect opinions from the PC companies on their BIM maturity statuses.

		Number of companies
	Content	
Level 0	Pencil and ink lines and text.	0
	Digital lines, text, blocks, and symbols in 2D.	5
Level 1	Simple 3D objects.	24
Level 2	3D building objects with unspecified information.	24
Level 3	3D building objects with requirements to objects, properties and ID.	0
	Manufacturer's 3D objects & properties for operation / FM.	0
	Digitisation	
Level 0	Drawings on transparent paper on a drawing table. Paper copies.	0
	Drawings made with 2D CAD in a computer. Paper copies.	5
Level 1	Drawings made with 3D CAD/BIM. Paper prints.	24
Level 2	Data hosted in the Common Data Environment (CDE).	24
Level 3	Drawings / views from BIM streamed to mobile devices. Limited paper use.	0
	Open BIM with dimensioning streamed to mobile devices.	0
	Interoperability	
Level 0	Drawing on plastic film copy of other disciplines drawings.	0
	Work on 2D DWG or DXF background from other disciplines.	5
Level 1	Work on 3D DWG background from other disciplines.	24
Level 2	File based sharing of open BIM (IFC) aggregated models.	24
Level 3	Sever-based sharing of open BIM (IFC), continuous validation of model.	0
	Sever-based communication & issue handling, all issues related to objects in BIM.	0
	Collaboration	
Level 0	Coordination in design meetings and onsite meetings.	5
	Systematic interdisciplinary controls with digital workflows.	0
Level 1	3D visualisation, visual controls in modelling tools.	24
Level 2	Systematic model coordination, clash detection, quantity take-off.	24
Level 3	Interface handling in BIM. Advanced simulations. Integrated Project Delivery (IPD).	0
	Model carry all information for construction and operation. Model driven production and assembly.	0

The BIM adopter's model

Technology adoption and innovation diffusion has been extensively studied. It is well established that companies can be categorised into: (1) innovators, (2) early adopters, (3) the early majority and (4) late majority and laggards, (Rogers, 1995).

To develop the BIM adopters' model, subjective opinions were used. The author found the respondents were not able to give a clear view how they behave towards new technologies. They mentioned that they would be willing to accept any new technology if it proved to be useful. In that case, the author judged them by the following rules: (1) the years of experience of the company in the industry. If the company has been in the industry for a long time but its BIM maturity was still low, there were reasons to believe the company was conservative towards new technology, thus in the group of late majority or laggards. (2) The records that the company has been involved in various innovation programs. For example, in Singapore, some PC companies are in the Integrated Construction and Prefabrication Hub (ICPH). ICPHs have advanced manufacturing facilities for PC panel production, with a high degree of mechanisation. These companies were assumed as active in new technologies adoption, thus risk takers. Below are the definitions and results:

Group level	Technology usage	Definitions	Number of companies
0	Late majority and laggards	Conservative and sceptical of innovation. They are concerned about their primary needs and security.	21
1	Early majority	Pragmatists. This group is secure to adopt new technology and innovation.	19
2	Early adopters	Enthusiasts and opinion leaders. They look for opportunity for leadership and recognition.	13
3	Innovators	Risk takers. They are driven by creativity.	0

Appendix D The meeting schedule with the key actors

Interviews were conducted at a designated time and mostly held at the PC manufacturer (PCM) factory for the convenience of the company's staff. Only milestone meetings were held at the Nanyang Technological University (NTU) campus. Generally, a set of predetermined open-ended questions were asked and as the dialogue continued, other questions pertaining to the topics were discussed as they emerged. Table D-1 presents the meeting the schedule with various actors. Due to confidentiality, the individual names cannot be mentioned.

- The purpose of the kick-off meeting was to introduce the team (e.g., technology vendor), align the goals, agree on the schedule and tasks ahead. The value stream mapping (VSM/A) tool to visualise and improve the current processes was also presented and discussed to ensure everyone was familiar with the approach.
- The evaluation of the present state of operations was achieved through numerous visits to the PC factory to conduct the interviews and discussions.
- Training and acceptance test of each system was completed before proceeding to the next area of focus. On average, it took the team between four to six months to develop the system.

Table D-1 Meetings schedule with the selected PC manufacturer

Date	Duration of meeting (hours)	Topic of discussion	Attendees/ designation	Location of meeting
27 Sep 2018	3	Part two research kick-off meeting. Team introduction and purpose of the study.	All PCM management and staff, RFID vendor and the author	NTU campus
5 Oct 2018	4	Approval of drawing present workflow interviews and VSM discussions.	Design engineer, draftsman, PCM management	PCM factory
9 Nov 2018	4	Status dashboard requirements and discussions – interview with design team.	Design engineer, draftsman, PCM management	PCM factory
23 Nov 2018	4	Production workflow and requirements – interviews and VSM discussions with production team.	Production manager and supervisor, the author	PCM factory
7 Dec 2018	3	RFID system and hardware requirements for production processes tracking – interview with production team.	Production supervisor RFID vendor, the author	PCM factory

21 Dec 2018	3	Approval of drawing system demonstration. Feedbacks gathering for further enhancement.	Design team, PCM management, the author	PCM factory
4 Jan 2019	8	RFID system pilot testing and training. Further discussion on requirements, stations to be tracked and data capturing approach.	Production supervisor, the author, RFID vendor	PCM factory
22 Jan 2019	6	Approval of drawing system training and acceptance tests.	Design team, PCM management, the author	PCM factory
26 Feb 2019	3	RFID status tracking - further discussion on requirements and system enhancement.	Production supervisor, the author, RFID vendor	PCM factory
5 Apr 2019	4	Inventory tracking – present workflow interviews and VSM discussions with logistic team.	Logistic staff, the author	PCM factory
11 Apr 2019	4	Delivery of inventory – present workflow, documentation and VSM discussions.	Logistic staff, the author	PCM factory
18 Apr 2019	4	Delivery of inventory – Proof of Delivery system requirements and expectations.	Logistic staff, the author	PCM factory
2 May 2019	3	Further discussions on tracking and delivery of inventory.	Logistic staff, the author	PCM factory
17 May 2019	4	Status dashboard requirements and discussions – logistic team interviews.	Logistic staff, PCM management, the author	PCM factory
24 May 2019	6	RFID system training and acceptance tests.	Production supervisor, the author, RFID vendor	PCM factory
14 Jun 2019	3	Identification of pilot projects, selection of precast panels to be tracked.	PCM management, the author	PCM factory
21 Jun 2019	3	Tracking and delivery system demonstration. Feedbacks gathering for further enhancement.	Logistic staff, the author	PCM factory
22 Jul 2019	3	Checkpoint meeting – update of part two development (1) Approval of drawing system and (2) Inventory tracking/delivery system.	The author, PCM management, RFID vendor	NTU campus
5 Aug 2019	4	Progress claims and payment – present workflow interviews and VSM discussions.	Planning co-ordinator, PCM management, the author	PCM factory
30 Aug 2019	6	Tracking and delivery system training and acceptance tests.	Logistic staff, PCM management, the author	PCM factory
6 Sep 2019	4	Progress claims and payment – present workflow, Further discussion on requirements.	Planning co-ordinator, logistic staff, the author	PCM factory
23 Oct 2019	4	Status dashboard requirements and discussions – planning team interviews.	Planning co-ordinator, PCM management, the author	PCM factory
31 Oct 2019	3	Progress claims and payment – present workflow, Further discussion on requirements.	Planning co-ordinator, logistic staff, the author	PCM factory

4 Dec 2019	3	Progress claims and payment system demonstration. Feedbacks gathering for further enhancement.	Planning co-ordinator, logistic staff, the author	PCM factory
19 Dec 2019	6	Progress claims and payment system training and acceptance tests.	Planning co-ordinator, logistic staff, the author	PCM factory

Table D-2 shows the sample of predetermined questions. It is worth noting that the probing questions were derived from the first part of the research, during the one-on-one interviews with the PC manufacturer. Essentially, rapport building involved mutual trust and respect between the interviewer and the subject-matter experts. It was through the connection between the author and interviewees (i.e., an established comfortable relationship) that enabled them to share their personal views, attitude and experiences of the topic of interests.

Table D-2 Sample of predetermined questions

Rapport building questions	<ul style="list-style-type: none"> • How many years have you been in this position? • Can you tell me the things you like most about your work? • What do you see as the most important responsibilities and tasks? • What are the important achievements you have attained since you took up this position?
Probing questions	<ul style="list-style-type: none"> • What are the current obstacles that prevent you from working effectively? • How effective do you think people collaborate in their work? • Looking at your present workflow, what would you have done differently, if anything? • What are the current ways of communicating with external and internal parties in project? • How much of visibility do you have in a typical PC project? • What are the areas of improvement in the pre-production phase? Be specific. • What are the areas of improvement in the post-production phase? Be specific.

Appendix E Functions of the PLMS system

The following sections provide a brief description of the current practice as well as the functions and features of the proposed PLMS system. Namely, System for Shop Drawing Approval (SSDA), System for Inventory Tracking and Delivery (SITD) with Proof of Delivery (POD), system for progress claims and payment (SPCP) and the status dashboard.

E.1 Shop drawing approval for PC production

Current practice

A typical shop drawing for PC production is shown in Figure E-1. The PC manufacturer will not start their casting work without formal approvals from the main contractor. As such, the master drawing list (MDL) is used to track the latest version of the approved shop drawings.

Figure E-1 Shop drawing for PC production

It comprises (1) the production submission date, (2) the approved date, and (3) the reason for the delay associated with both the submission and decision. The current practice is to manage the MDL with spreadsheet that reside in individual computer. Such approach is proven to be tedious, time consuming and prone to human errors, especially when the number of drawings increase.

Deployment of SSDA system with BIM to improve the current workflow

The actual deployment of the SSDA system is shown in Figure E-2. With the information extracted from the BIM model, the system is able to automate the generation and monitoring of the master drawing list (MDL). Once the data are uploaded to the BIM cloud, it facilitates information sharing among stakeholders and helps streamline the shop drawing approval process. The author has adopted a simple design approach to ensure easy learning and usage. Consequently, the bespoke system provides an intuitive interface for user to access its key functions.

Figure E-2 Actual deployment of the SSDA system

Figure E-3 shows the screenshot of the main page of the SSDA system (sensitive information has been greyed out). The following sections provide details and purposes of four key features, namely (1) master drawing list, (2) transmittal, (3) grouping and (4) sync folder.

1 MASTER DRAWING LIST
2 TRANSMITTAL
3 GROUPING
4 SYNC FOLDER

- 001 RV Shop Drawings
 - Approved Drawing
 - Connection Detail
 - CAD
 - PDF
- Layout Plan
- PC Panel

Refresh

Properties

ID:

Filename:

Version:

Step 1: File

Grouping Name:

Name: (DETAIL-15_RF)
[Prefix] [Panel Marking]

Step 2: Revision

Current:

☐ New:

New Submission Date:

Step 3: Approval

Status:

Approved Date:

Step 4: Production

Last Submitted Date:

☐ New Submission Date:

Figure E-3 Users interface of the SSDA system

1. **Master Drawing List (MDL):** it is a list that tracks the revision of each shop drawing submitted for review. As the project progresses, the MDL is to be submitted as a part of the monthly update report.

Revno	DWG NO. CSP001	DRAWING TITLE	RVD TO KSH	LATEST REV	DATE OF SUBMISSION										APPROVAL - ARUP			
					00	01	02	03	04	05	06	07	08	09	10	DATE		STATUS
		CONTENT SHEET																
	KSH_ST_SHD_C_10773.06.C8	T3-4BL10-2REV_01	22-04-2019	00	22-04-2019													
	KSH_ST_SHD_C_10774.06.C8	T3-4BL11-1REV_02	22-04-2019	00	22-04-2019													
	KSH_ST_SHD_C_10775.06.C8	T3-4BL11-2REV_02	22-04-2019	00	22-04-2019													
	KSH_ST_SHD_C_10796.08.C8	T3-4BL4-1REV_02	22-04-2019	00	22-04-2019													
	KSH_ST_SHD_C_10797.08.C8	T3-4BL4-2REV_02	22-04-2019	00	22-04-2019													
	KSH_ST_SHD_C_10798.07.C8	T3-7BL5-1REV_01	22-04-2019	00	22-04-2019											22-04-2019	RAA	
	KSH_ST_SHD_C_10800.07.C8	T3-7BL1-1REV_02	22-04-2019	00	22-04-2019											22-04-2019	O	
	KSH_ST_SHD_C_10801.07.C8	T3-7BL1-2REV_02	22-04-2019	00	22-04-2019											22-04-2019	RS	
	KSH_ST_SHD_C_10802.08.C8	T3-4BL10-1REV_02	22-04-2019	00	22-04-2019													
	KSH_ST_SHD_C_10803.08.C8	T3-4BL10-2REV_02	22-04-2019	00	22-04-2019													
	KSH_ST_SHD_C_10804.08.C8	T3-4BL13-1REV_01	22-04-2019	00	22-04-2019													
	KSH_ST_SHD_C_10805.08.C8	T3-4BL13-2REV_01	22-04-2019	00	22-04-2019													
	KSH_ST_SHD_C_10812.00.C8	T3-1BL11-1REV_01	22-04-2019	00	22-04-2019													
	KSH_ST_SHD_C_10813.00.C8	T3-1BL11-2REV_01	22-04-2019	00	22-04-2019													
	KSH_ST_SHD_C_10845.06.C7	T2-4BL1-1REV_04	22-04-2019	00	22-04-2019													
	KSH_ST_SHD_C_10846.06.C7	T2-4BL1-2REV_04	22-04-2019	00	22-04-2019													
	KSH_ST_SHD_C_10848.06.C7	T2-4BL10-2REV_01	22-04-2019	00	22-04-2019													
	KSH_ST_SHD_C_10849.06.C7	T2-4BL11-1REV_01	22-04-2019	00	22-04-2019													
	KSH_ST_SHD_C_10871.08.C7	T2-4BL12-1REV_03	22-04-2019	00	22-04-2019													
	KSH_ST_SHD_C_10872.08.C7	T2-4BL12-2REV_03	22-04-2019	00	22-04-2019													
	KSH_ST_SHD_C_10873.07.C7	T2-7BL4-1REV_01	22-04-2019	00	22-04-2019													

Figure E-4 Example of the MDL in SSDA

Figure E-4 provides a screen shot of the MDL created from the BIM model and hosted in SSDA. Since the SSDA system is developed on a BIM cloud enabled platform, the key benefits are: (1) information hosted securely in central repository, instead of spreadsheet in individual PCs. (2) All revisions are updated automatically, eradicating human errors. The SSDA system allows users to export the MDL information for reporting purpose.

2. **Transmittal:** a transmittal is a brief letter, typically with a document attached to explain the contents. Transmittals are often used in construction companies as a necessary communication tool in projects where a large number of documents are involved. SSDA is able to generate transmittals along with packages of document for transfer. From the viewpoint of the PC manufacturer, it is a formal means of sending shop drawings, models and other documents to another project member within the company or to external parties (in this case, the main contractor). Figure E-5 shows the screen shot of the internal and external transmittal generated by SSDA.

INTERNAL TRANSMITTAL					
Ref: R J 9 9 9 0 0 1 <small>project code serial no</small>					
Date: 05-10-2018					
To: DOM					
Re: PLQ-PC					
Attached herewith the following drawings / documents:-					
No	Drawing No	Rev	Description	Size	Set
1	KSH_ST_SHD_C 9079.02 C2	01	Planter (2_PL_01)	A3	1
2	KSH_ST_SHD_C 9080.02 C3	02	Planter (2_PL_02)	A3	1
3	KSH_ST_SHD_C 9081.02 C3	00	Planter (2_PL_03)	A3	1
Others _____					
☒ For Production ☐ For Mould Fabrication ☐ For Information ☐ As Requested ☐ Others _____					
Approved by:			Received by:
<small>Signature / Name</small>			<small>Signature / Name / Date</small>		
IP-SYS-04 Rev 01 Appendix 5					

EXTERNAL TRANSMITTAL					
Ref: TR-RJ999-01					
Date: 05-10-2018					
To: KSH Site Office					
Attn: Mr. Jianxiang					
Dear Sir/Madam,					
Re: KSH-Precast Wall (T1)					
We forward herewith the following drawings / documents:-					
No	Drawing No	Rev	Description	Size	Set
1	KSH_ST_SHD_C 9079.02 C2	01	Planter (2_PL_01)	A4	1
2	KSH_ST_SHD_C 9081.02 C3	00	Planter (2_PL_03)	A4	1
☐ For Approval / Comment ☐ For Record / Retention ☒ For Information / As Requested ☐ For Quotation / Tender ☐ Others _____					
Approved by:			Received by:
<small>Signature / Name</small>			<small>Signature / Name / Date</small>		
IP-SYS-04 Rev 01 Appendix 6					

Figure E-5 Internal and external transmittal

The content in a transmittal can be:

- Reference number.
 - Date of the sending.
 - Name details of sender/company and recipient/company.
 - Project name, number(s), and other references to the project.
 - List of files sent: file name, revision number and other relevant information.
 - Reason(s) for the transmittal.
3. **Grouping:** it allows PC manufacturer to categorise the various PC panels into specific groups. A group indicated the type of particular precast component. For instance, group name: ‘CO’ is column, ‘BA’ is bay window and so on. This feature enables users to add, update or delete grouping name accordingly. Grouping prepares the PC manufacturer for batch production.
4. **Sync all files:** this function consolidates all the approved shop drawings that reside in the BIM-cloud and download them to the PC manufacturer’s system. It allows the engineer to manage the revisions and update the PC production department accordingly.

E.2 The tracking and delivery of inventory

Current practice

Current tracking process involves tagging of panel by labelling the PC panels as shown in Figure E-6. The PC panel is tagged immediately after the final inspection. However, as the number of panels increase, such manual process creates numerous challenges for the PC manufacturer. For example, panels become difficult to locate and in worst case scenario, need to be recast for urgent delivery. This creates unnecessary work and additional cost to the PC manufacturer.

Figure E-6 Current tracking method of inventory

The delivery process commences once the delivery order is received. The PC panels are loaded onto the vehicle as shown in Figure E-7. However, misplacement of paperwork, or human error in documentation may occur. Furthermore, due to the lack of visibility of the actual delivery process, the PC manufacturer has challenge knowing the status and location of specific panels.

Figure E-7 Current delivery process

Deployment of SITD and POD system to improve workflow

Working in tandem, the SITD and POD address some of the pertinent concerns of PC manufacturer. The actual deployment of the SITD system is shown in Figure E-8. Inventory search can either perform by (1) Query on the 3D IFC data model or (2) search PC panel by its unique identity.

Figure E-8 Location of inventory via SITD system

The POD system digitises the delivery process and eliminates unnecessary paperwork from the operation. The delivery workflow with the support of the POD system, comprises three key functionalities, (1) ready to ship sign-off, (2) recipient sign-off and (3) digitised D/O:

1. **Ready to ship sign-off:** the PC manufacturer acknowledge the completion of the loading process and ready to ship out. The following steps are taken. Figure E-9 shows the screenshot of the “to-ship” function.

- a. PC panels to be delivered are scanned, and the PC panels’ ID are indicated in the handheld device.
- b. Any additional instruction or remark for the recipient is added.
- c. Finally, the logistic staff sign-off the items, ready for delivery.

The screenshot shows a handheld device interface for the 'To-ship' function. The screen is divided into several sections:

- Menu:** DELIVERY BARCODE/ QRCODE (TO SHIP)
- Item ID:** AMK23NH (Demo)
- Status:** In-Transit
- Company:** Trimble Solutions SEA Pte Ltd
- QR Code:** A large QR code is displayed.
- Item List:** Two items are listed: 'QR00000010, PC' and 'QR00000010_-xxx, PC'. Each item has a 'Remove' button next to it.
- ATTENTION NAME:** chester
- INSTRUCTION:** Please check the item once received
- Vehicle No/ Prime Mover:** PC 1120C
- Trailer No:** TL 302
- Time arrives at factory:** 13:50
- Time leaves at factory:** 14:21
- SIGN OFF (PRECASTER):** A signature field with a 'Clear' button and an 'OK' button.

Annotations on the left side of the screen point to specific sections:

- PC panels to be delivered:** Points to the item list section.
- Instruction or remark (as necessary):** Points to the instruction field.
- Sign-off for delivery:** Points to the signature field.

Figure E-9 “To-ship” function of POD system

2. **Recipient sign-off:** the main contractor acknowledge the PC panels are received. The following steps are taken. Figure E-10 provides the screenshot of the “to receive” function

- a. The PC panels are scanned and updated as “received”.

- b. Any remark or additional information for the PC manufacturer can be recorded accordingly.
- c. Finally, the recipient sign-off to indicate that the items have been delivered.

The screenshot shows a mobile application interface for the 'To-receive' function of the POD system. The interface is divided into several sections, with annotations pointing to specific fields:

- PC panels received:** Points to the 'ITEM' section, which displays 'QR00000010, PC' and 'QR00000010_XXX, PC'.
- Remark (if necessary):** Points to the 'REMARKS' section, which contains the text 'Items received'.
- Additional information (if necessary):** Points to the 'ADD PHOTO' and 'ADD MILL CERTIFICATE' sections, which are currently empty.
- Sign-off upon receive of PC panels:** Points to the 'SIGN OFF' section, which features a signature field and a 'Clear' button.

Other visible fields include 'DELIVERY BARCODE/ QR CODE (TO RECEIVE)', 'AMK23NH (Demo)', 'Delivered', 'DOI100000052', 'Grab', 'Time arrives on site' (17:52), and 'Time leaves site' (19:14).

Figure E-10 “To-receive” function of POD system

3. **Digitised D/O:** the D/O is stored in BIM cloud platform for future retrieval. It can be used for progress claim and payment. Figure E-11 shows the screenshot of the digitised D/O.
 - Comprises general customer information and the PC panels’ delivery details.
 - The acknowledgement of both PC manufacturer and main contractor are presented in the D/O.

DO1100000002

1 of 1 Find | Next

To:

Attn:

Project:

Instruction:

Delivery Order

D/O No:

D/O Date:

P/O No:

Project No:

SN	Description	Blt/ Zone/ Sector	Level	Cast Date	Weight (t)	Qty
Vehicle No/ Prime Mover: <input type="text"/>						
Vehicle No/ Prime Mover: <input type="text"/>						
Time arrives at factory: <input type="text"/>						
Time leaves at factory: <input type="text"/>						
Time leaves on site: <input type="text"/>						
Time arrives on site: <input type="text"/>						
REMARKS: <input type="text"/>						
ATTACHMENT(S): <input type="text"/>						
Acknowledged & Issued by: <input type="text"/>						
Acknowledged & Checked by: <input type="text"/>						
Acknowledged & Received by: <input type="text"/>						

Figure E-11 Digitised D/O

E.3 Progress claims and payment

Current practice

Figure E-12 shows the actual filled out document ready for progress claim submission (sensitive information pertaining to the company, the project and the detail amount of the claim have been greyed out). Currently, the creation of panel list is done manually, it is time-consuming and can be error prone. As the number of PC panels increases, it become challenging to track and update the status of each claim.

Figure E-12 Actual claim document

Figure E-13 shows the currently format used in a typical progress claim and payment process. Currently, the planning co-ordinator is required to manually keep track of the PC panels delivery status, claim status (i.e., previous claims, so that the balance amount can be accrued to the next claim or “accumulated” claim) as well as the number of PC panels in the project. The amount of information in the list will continually increase as the production and delivery progress.

Progress Claim No. 10- Precast Elements

Item	Description	Unit	Qty	Rate	Amount	Previous Claim		Current Claim		Accumulated Claim	
						Amount Delivery (100%)		Amount Delivery (100%)		Amount Delivery (100%)	
						Qty	\$\$	Qty	Amount	Qty	Amount
SUPPLY OF PRECAST ELEMENTS											
	Supply, fabrication and delivery of precast concrete elements in accordance with the ARUP's design and detail including installation of all cast-in items (materials by KSH)										
	Rubbish Chute										
1	All Levels; Precast rubbish chute & internal lining	m									
	Precast concrete stair flight										
2	To Level 1 to 17; PC stair flight	m3									
	Structural Precast Walls										
3	Precast wall 200mm thick - structural	m2									
4	Precast wall 250mm thick - structural	m2									
5	Precast wall 300mm thick - structural	m2									
	Precast Planks										
6	Level 6 to 15; 70mm thick precast plank	m2									
	Level 6 to 15; 70mm thick precast plank										
	Columns										
7	Level 6 to Roof	m3									
	Precast Beams										
8	Level 6 to 15	m3									
	Precast Balcony										
9	Level 6 to 17; Types 1 to 4; 200mm thk	m3									
	Precast A/C Ledge										
10	Level 6 to 17; 150mm thk	m3									
	Precast RC Ledge										

Figure E-13 The format for manual calculation of progress claim

Deployment of SPCP system to improve progress claim and payment workflow

To bring about improvement, the proposed SPCP system can re-engineer the progress claim and payment workflow by applying relevant IT to streamline the key tasks. Figure E-14 shows the quantity-take-off from a BIM model. It allows user to accurately extract the panel list from the 3D model for claim calculation.

Figure E-14 BIM model for quantity-take-off

Figure E-15 presents the claim calculation function provided by the SPCP system. User can easily generate an official claim form for submission to the main contractor.

Figure E-15 Claim calculation and form generation

E.4 Functions of the status dashboard

The web-based status dashboard is an interface to the various project activities, providing vital information to users (e.g., the status of the PC panel) during the construction phase.

Figure E-16 presents the functions of the dashboard:

1. Display filtering function enable the IFC data model to be visualised by locations or by floor.
2. By means of colour mapping technique, real-time status of the PC panels are displayed. For instance, “blue” represents manufactured, “red” represents in-transit, “green” represents delivered and “purple” represents installed.
3. PC panel information. Once a specific item is selected, information such as panel marking, type of panel, date & time as well as last status are displayed.
4. It provides a real-time view of the overall status of the construction project. The percentage of completion by floor levels is presented.

Numeric chart options provide real-time project metric updates

5. “Live” update of the status and percentage of completion progress for each PC panel. The dashboard provides status update according to the key stages such as (1) manufactured, (2) in-transit, (3) delivered, (4) rework and (5) installed.
6. Percentage of completion donut chart of each status. For instance, PC manufacturer can obtain real-time update of the percentage of PC panels installed. This information will be useful for progress claims.