Game Theory Analysis of Intervention Strategies to Overcome Barriers in BIM Implementation: A Study on Contractor Firms

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Game Theory Analysis of Intervention Strategies to Overcome Barriers in BIM Implementation: A Study on Contractor Firms

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Preface

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Summary

Building Information Modeling (BIM) has emerged as a transformative solution for enhancing productivity and streamlining the construction industry. It represents a digital representation of a facility's physical and functional characteristics, serving as a shared knowledge resource throughout the entire life cycle of a project. In Singapore, the government, led by the Building and Construction Authority (BCA), has significantly promoted BIM adoption through various initiatives, including a five-year BIM adoption roadmap and subsidies for implementation costs. These endeavors have resulted in notable improvements, with BIM adoption rates increasing from 20% in 2009 to 65% in 2014. However, despite these achievements, barriers to BIM implementation within construction firms in Singapore persist. This research aims to identify these barriers, propose effective solutions, and evaluate their effectiveness using game theory in a collaborative organizational context.

To achieve the objectives, a comprehensive research methodology was employed. The study commenced with a thorough survey to assess the current level of BIM implementation within construction firms and identify the key actors involved in the BIM process. Subsequently, in-depth interviews were conducted with these key actors, incorporating insights from literature reviews and the survey findings. The interviews aimed to identify the barriers encountered during BIM implementation. Based on the common barriers identified, the research team designed specific interventions to address and overcome these challenges. Game theory was applied to determine the most effective intervention, considering shared benefits and costs. The ultimate goal was to identify the intervention that would yield the best overall outcome for the organization.

The study's findings revealed varying BIM maturity scores across different categories and sub-categories. The overall average BIM maturity score for the organization was 3.21 on a scale of zero to five. Notably, the highest maturity score was observed in the ICT Infrastructure and Strategy category, indicating that the companies recognized the benefits of BIM and had invested in manpower and facilities. However, the lowest maturity score was recorded in the category of Data Structure, indicating a need for improvement in data organization and exchange quality within the firms. Furthermore, the research highlighted the significant involvement of key departments in BIM implementation, including BIM, Planning, Quantity Surveying (QS), and Finance. These departments played crucial roles in collaborating to ensure successful BIM integration. Collaboration scenarios centered around project schedule monitoring and control, cost estimating and budgeting, project cash flow monitoring and control, and company cash flow monitoring and control.

Through the interviews and analysis, four prominent barriers to BIM implementation were identified. The first common barrier was the difficulty in aligning objectives and promoting collaboration among different departments within the construction firms. The second barrier stemmed from the learning curve of digital tools and technologies, which required substantial training and adjustment. The third barrier involved lacking well-established and customized digital tools aligned with local work practices, impeding seamless integration. Lastly, the increased hardware and software specifications required to view complex BIM models added to the challenges, often demanding significant investments.

To overcome these barriers, four interventions were proposed based on the input from the involved departments. The most frequently suggested intervention was establishing a specialist group focused on collaboration and integration. This group would act as facilitators, bridging the gap between departments, providing guidance, and offering training on BIM integration. By improving technical understanding and alleviating time pressures during the transition, this intervention aimed to reduce resistance to change. The second intervention involved establishing a comprehensive training program and knowledge-sharing sessions among departments to enhance overall knowledge and understanding of BIM and its implementation. The third and fourth interventions focused on developing in-house software and allocating additional budget for BIM facilities. These measures aimed to reduce the learning curve for non-BIM staff, seamlessly integrate BIM into existing workflows and enhance the organization's ability to operate and extract data independently. These proposed interventions align with previous studies and can be applied by similar firms, considering their BIM capabilities and available resources.

The evaluation of the interventions indicated that all four effectively addressed the identified barriers to BIM implementation. However, it was found that allocating additional budget for BIM facilities and providing additional training had the least impact on overcoming the barriers, as the benefits did not consistently outweigh the costs. This finding resonates with the concerns of construction firms regarding the costs and benefits associated with BIM implementation. On the other hand, the interventions involving the formation of specialist groups and the development of in-house software proved highly effective in aligning workflows, reducing resistance to change, and maximizing the benefits of BIM.

Abstract

Building Information Modeling (BIM) is recognized as a revolutionary solution to enhance productivity and streamline construction processes. Despite significant efforts by the Singaporean government to support BIM implementation, barriers persist. However, there needs to be more research focusing on identifying and evaluating barriers and proposing solutions at the organizational level. This thesis aims to address this gap by identifying barriers within the organizational context, proposing solutions, and evaluating their effectiveness using game theory. The research commenced with a survey to assess the current level of BIM implementation and identify key actors involved in the process. This provided insights into the BIM capacities of contractors. Barriers to BIM implementation were then identified through interviews with significant actors, as identified through literature review and survey. Based on the most common barriers, interventions were designed to overcome these challenges. Game theory was subsequently employed to evaluate the effectiveness of these interventions, considering shared benefits and costs. Results demonstrated the importance of BIM-specific users, both technical and non-technical, within the contractor's firm. Implementing BIM within the company revealed four prominent barriers experienced by different departments. These barriers were categorized as difficulties in aligning objectives and collaboration among departments, learning curve associated with digital tools and technologies, lack of well-established and customized tools aligned with local work practices, and increased hardware and software specifications to view large BIM models. The departments commonly suggested four interventions to overcome these barriers. Creating a specialist group focused on collaboration and integration was the most frequently proposed intervention, acting as facilitators to bridge departmental gaps and provide guidance and training on BIM integration. A training program and knowledge-sharing sessions were proposed as the second intervention to enhance overall BIM knowledge and understanding among departments. The third and fourth interventions focused on developing in-house software and allocating additional budget for BIM facilities, aimed to reduce the learning curve for non-BIM staff, integrate BIM into existing workflows, and enhance data inter-dependence. However, the study found that allocating additional budget and providing additional training had limited impact, while the establishment of specialist groups and developing in-house software effectively aligned workflows, reduced resistance to change, and enhanced BIM benefits.

Keywords: BIM, barriers, solutions, game theory, collaboration

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1. Introduction

This chapter consist of the problem definition in Section 1.1, the research question in Section 1.2, and the research approach in Section 1.3. Subsequently, the motives for undertaking this thesis are discussed in Section 1.4. Finally, Section 1.5 provides a reading guide to navigate the thesis.

1.1. Problem Definition

The construction industry is known for its inefficiency and lack of trust (Latham, 1994; Egan, 1998; Gallaher, 2004), with a fragmented and adversarial nature (Khee, 2011). This fragmentation leads to project execution inefficiencies as participants focus on individual tasks and overlook their impact on the overall project (Baiden, 2006; Froese, 2010). Furthermore, the increasing complexity of construction projects poses challenges in management (Alshawi & Ingirige, 2003; Chan et al., 2004; Williams, 2002). To address these issues, collaborative project delivery approaches such as Building Information Modeling (BIM), Virtual Design and Construction (VDC), and Integrated Digital Delivery (IDD) have been established to improve project performance.

Building Information Modeling (BIM) is considered the next-generation solution for enhancing productivity in the construction industry and streamlining building delivery processes through improved data interoperability. BIM could be utilized from the early design stages through construction, operation, and maintenance phases. It offers advantages such as faster delivery, improved coordination, cost reduction, higher work quality, enhanced safety and risk management, and increased productivity. The construction industry has gradually embraced BIM, with top consultancy and contractor companies adopting this transformative technology. Initially a visual aid for architects, BIM has evolved into a dynamic tool applicable to projects of all sizes, involving stakeholders from various disciplines. Singapore's public sector, led by the Building and Construction Authority (BCA), has taken the lead in promoting BIM implementation through a five-year plan.

Virtual Design and Construction (VDC) involves managing BIM models, people, and processes to achieve project or organizational goals and improve performance. The core principle of VDC is the "build twice: first virtual, then real" framework, consisting of four phases: design, construction coordination, virtual planning, and execution. This approach requires stakeholders to collaborate and work towards common goals by systematically modeling, rehearsing, and building the project while continuously measuring and reducing deviations between the real and virtual aspects. VDC offers significant benefits to both consultants and contractors in terms of increased productivity in design and construction phases. It helps reduce design errors and communication delays, enhances construction safety and site management, and overall improves project productivity. By embracing VDC, stakeholders can leverage its capabilities to streamline processes, enhance collaboration, and achieve better outcomes in construction projects (Building and Construction Authority, 2017; Li et al., 2009)

Introduced by the Building and Construction Authority of Singapore (BCA) in October 2017, Integrated Digital Delivery (IDD) is a concept built upon the principles of BIM and VDC. IDD aims to integrate work processes and connect stakeholders involved in a construction project

throughout its entire lifecycle, including design, fabrication, on-site assembly, and building operations and maintenance. The framework of IDD comprises four phases: Digital Design, Digital Manufacturing and Fabrication, Digital Construction, and Digital Asset Delivery and Management. To drive digitalization in Singapore's construction industry, BCA launched IDD, offering training programs, a digital platform, and collaborative pilot projects with private sector developers. These initiatives aim to facilitate the adoption of IDD technologies throughout the project lifecycle. In collaboration with the Infocomm Media Development Authority (IMDA), BCA and IMDA have called for the development of a digital construction platform that fosters collaboration among stakeholders. This platform will streamline communication, enhance coordination, and facilitate the seamless integration of digital technologies in construction projects. Through the implementation of IDD, Singapore's construction industry aims to leverage digital advancements to improve project delivery, enhance productivity, and optimize the overall building lifecycle. The efforts of BCA, stakeholders, and training programs are instrumental in driving the digital transformation of the industry and positioning Singapore as a leader in integrated and digitally-driven construction practices (Building and Construction Authority, Infocomm Media Development Authority, 2018).

Despite the potential of Integrated Digital Delivery (IDD) in the construction industry, there is limited research available on its implementation and current level of adoption compared to Building Information Modeling (BIM) and Virtual Design and Construction (VDC). A recent study conducted by Hwang et al. (2020) focused on IDD implementation rates and the perceived improvements in project performance, cost, time, and quality. The study revealed that IDD implementation in the Singaporean construction industry is relatively low, with only 38.71% of organizations having implemented IDD technologies across all four phases. Respondents generally agreed that IDD implementation brought about improvements in overall project performance, cost, quality, and schedule, with average percentages of 5.15%, 3.76%, 4.48%, and 4.44% respectively. However, the adoption rate of individual IDD technologies was found to be relatively low, averaging at 20.67%, indicating slow technology adoption in the construction industry, as highlighted in previous research.

Nevertheless, the study by Hwang et al. (2020) showed a positive outlook for IDD implementation, as only 12.90% of organizations reported not having implemented any IDD technologies. This positive trend can be attributed to the Singapore government's efforts in promoting and developing BIM capabilities within the construction industry over the years. Singapore's construction industry has been recognized as relatively mature and advanced in BIM adoption. Since IDD builds upon BIM, enhancing BIM implementation has a significant positive impact on promoting the adoption of IDD.

In this context, contractors play an essential role in the BIM adoption process for projects, as highlighted by Hwang et al. (2020). With the prevalence of design and build contract types, contractors are responsible for realizing, implementing, and fulfilling the BIM goals and objectives set by the client. While local contractors have shown improvement in their BIM collaboration capabilities through the use of advanced BIM tools and processes, there are still

significant barriers to fully harnessing the potential of BIM in enhancing productivity and efficiency.

1.2. Research Question

1.2.1. Problem analysis and research question

Successful BIM implementation in construction projects requires integration and collaboration among all stakeholders. While inter-firm collaboration has received considerable attention, collaboration within organizations remains underexplored (Sun & Wang, 2019; Hochscheid & Halin, 2019). This thesis focuses on studying a general contractor in Singapore, given their pivotal role in coordinating diverse disciplines. Previous studies have identified barriers to BIM implementation, including management support, people and culture, technology, and adherence to defined processes and standards. Furthermore, the organization's BIM maturity level influences the barriers encountered during implementation (Siebelink, 2020).

The following problem definition summarizes the information above:

The pivotal role of a general contractor in achieving successful BIM implementation within the construction process cannot be overstated. While BIM has gained widespread adoption in Singapore's construction industry, it is crucial to recognize the significant barriers faced by contractor firms that hinder their progress in fully embracing BIM. In order to advance and mature in terms of BIM utilization, it is imperative to delve into the specific challenges these organizations encounter during their BIM implementation endeavors and explore effective strategies to overcome them. By understanding and addressing these barriers, contractor firms can unlock the immense potential of BIM and propel themselves towards enhanced productivity, efficiency, and overall project success.

The aim of this research is to propose solutions to enhance the implementation of Building Information Modeling (BIM) within the context of large Singaporean contractors. The study seeks to identify appropriate implementation strategies that can effectively address the barriers associated with BIM. The following research question guides the investigation:

What are the potential solutions to address the barriers encountered by large contractor firms in Singapore during the implementation of BIM, and what is the effectiveness of these solutions in mitigating or reducing these barriers?

1.2.2. Research objectives

The research objectives are to find out which solution yield the best net benefit in overcoming barriers experienced by actors within general contractor firm in Singapore. Cooperative game theory would be used as a framework since it is able to simulate various scenario with different intervention; therefore, the most suitable intervention could be identified. The cooperative nature of a game is analogous to the collaborative nature of the building information modeling (BIM) process in the contractor firm, where employees from different departments are working together to achieve the common BIM goal.

The following research sub-question is formulated to fulfil the research objective:

1. What is the current level of BIM capacities of the organization?

2. What are the actors that involved and benefitted in the BIM process?

3. What are the barriers (difficulties) experienced by the actors during the BIM process?

4. What are the solutions for the above difficulties, and what is the effectiveness of these solution(s)?

1.3. Research Approach

The systematic methodology employed in this study consisted of several essential steps, which are summarized in Table 1.1, providing an overview of the research methods utilized for each outcome.

First and foremost, a comprehensive literature review was undertaken to acquire a thorough understanding of the subject and establish the necessary background information. This review served as the foundation for subsequent data collection and analysis. Next, a survey was conducted to evaluate the current extent of Building Information Modeling (BIM) implementation and determine the capacities of the participating contractor firms. In-depth interviews were then carried out with selected actors to delve deeper into the barriers encountered during BIM implementation. These qualitative interviews provided valuable insights into the challenges faced by the actors, enabling a detailed exploration of the barriers. The data obtained from the interviews were utilized to identify the most prevalent barriers to implementation. Based on these findings, interventions were developed to address and overcome the challenges. The interventions were specifically designed to mitigate the impact of the barriers and enhance BIM implementation within the contractor firms.

To assess the effectiveness of the interventions, game theory was employed. This analytical approach facilitated the evaluation and comparison of potential outcomes and payoffs associated with each intervention. The objective was to determine the intervention that would yield the highest overall payoff for the organizations, taking into consideration the shared benefits and associated costs.

Table 1.1: Overview of Research Method

Outcome	Type of data	Research method
BIM Maturity of Organization	Quantitative	Survey
Major actors	Qualitative	Literature review and Interview
Possible coalition of actors	Qualitative	Interview
Barriers experienced	Qualitative	Interview
Possible intervention	Qualitative	Interview
Utilities of benefit sharing game	Quantitative	Survey
Utilities of cost sharing game	Quantitative	Survey
Return on investment on intervention	Quantitative	Game theory

The research model, as illustrated in Figure 1.1, outlines the sequential flow of the methodology, starting from the literature review and progressing through data collection, barrier identification, intervention design, and intervention effectiveness evaluation.

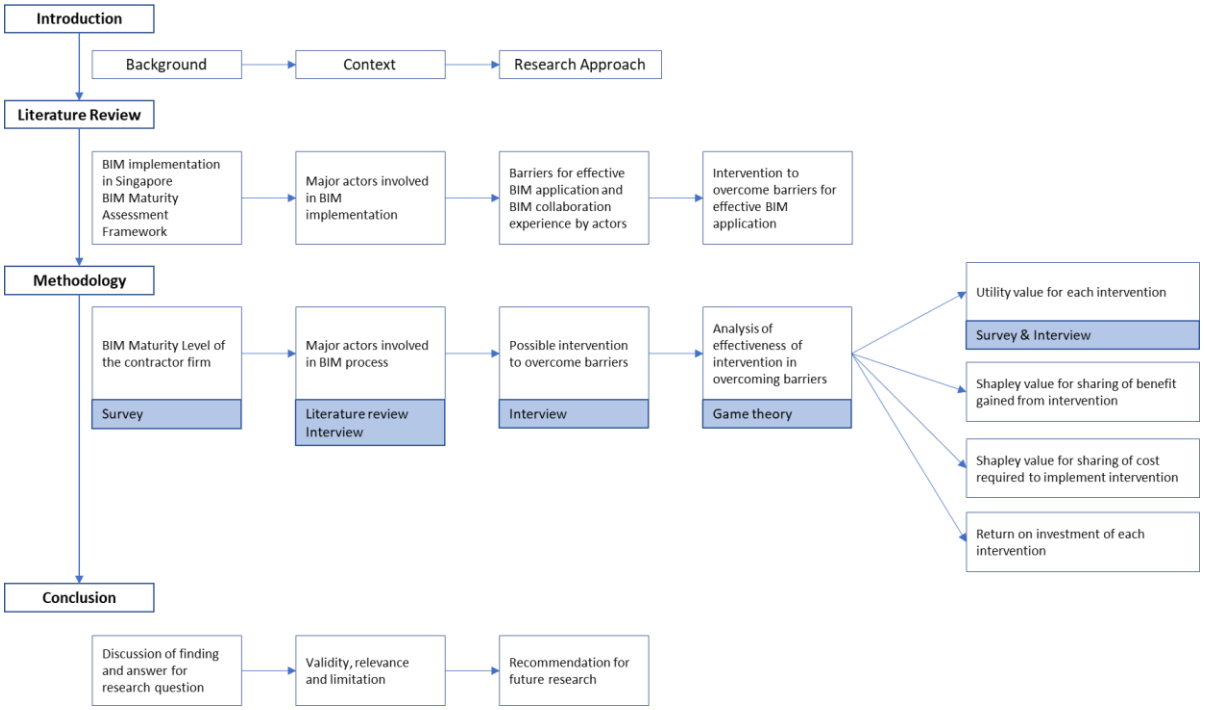


Figure 1.1: Research Model

1.4. Significance and Rationale of Research

In Singapore, the adoption of Building Information Modeling (BIM) has been driven by a top-down approach led by the Building and Construction Authority (BCA). The BCA has implemented various initiatives, including a five-year BIM adoption roadmap and subsidies for the implementation costs, to promote BIM within the local construction industry. Additionally, the government has introduced BIM Particular Conditions to guide industry procedures, roles, intellectual property rights, and contractual agreements related to digital data processing and reliance on 3D models. These efforts have resulted in a significant improvement in BIM adoption rates, increasing from 20% in 2009 to 65% in 2014. Singapore's leadership in BIM implementation in Asia is evident through the issuance of 12 out of 35 BIM standards in the region (Cheng & Lu, 2015). Despite the relatively high adoption rate, the construction industry in Singapore is experiencing a notable lack of significant productivity improvement, estimated at a mere 5% (Hwang at al., 2020). This glaring disparity clearly indicates the presence of significant barriers impeding the effectiveness of BIM implementation. These barriers hinder the industry's ability to fully capitalize on the potential benefits offered by BIM technology. It is crucial to address these obstacles promptly to unlock the true transformative power of BIM in the Singapore construction sector, enabling substantial productivity gains and enhancing overall project outcomes.

While productivity in the construction industry has been extensively studied, with some research focusing on the impact of BIM on productivity, critical challenges and possible solutions of productivity measurement (e.g. (Hwang et al., 2020; Liao et al., 2020), studies tend to emphasize project-wide, inter-firm collaboration rather than intra-firm collaboration. However, intra-firm collaboration is the foundation for effective inter-firm collaboration

(Hochscheid & Halin, 2019). Although there have been studies on internal BIM collaboration whin construction firm in the global construction industry, no comprehensive research has specifically examined the barriers to BIM implementation within construction firm in Singapore.

To address these gaps, this study aims to analyze the barriers to BIM implementation at the individual actor level within a contractor firm in Singapore. The study adopts a narrower scope, considering specific workflows, cultural factors, technical expertise, and the maturity of BIM adoption. It also evaluates the effectiveness of interventions to overcome these barriers using cooperative game theory. By modeling the strategic interactions between different actors in a collaborative setting, game theory enables the comparison and testing of various implementation strategies to identify the most effective approach. This research contributes to a more practical understanding of proposed solutions and fosters better BIM implementation in contractor firms.

1.5. Reading Guide

Chapter 1 sets the stage for this thesis by providing the contextual background and introducing the research question and objectives. The research approach and the underlying motive for conducting this study are also discussed.

Moving to Chapter 2, a comprehensive literature review is presented. This review covers various aspects such as the definition of Building Information Modeling (BIM), assessments of BIM implementation, BIM implementation in the Singaporean context, essential actors involved in the BIM process, barriers and drivers of BIM implementation, and interventions to overcome these barriers. This literature review forms the theoretical framework of the thesis.

Chapter 3 describes the research methodology employed in this study. It explains how the BIM maturity level was determined (sub-question 1), how significant actors were identified (sub-question 2), and how the barriers experienced by these actors were uncovered. Additionally, the chapter discusses the design of interventions to overcome these barriers (sub-question 3). It also provides an overview of game theory and its application in evaluating the effectiveness of different interventions in addressing the research sub-question 4.

Moving forward, Chapter 4 presents the findings from the investigation conducted using the various methods mentioned earlier. These findings elaborate on the BIM maturity level, the significant actors involved, the barriers experienced, and the effectiveness of the interventions.

Chapter 5 critically examines the results obtained, discussing their validity, generalizability, and limitations. It provides a comprehensive analysis of the findings, highlighting their implications and addressing potential limitations of the research

Finally, Chapter 6 draws conclusions based on the overall findings and offers recommendations for future research. It also provides practical recommendations for the implementation of BIM in large contractor firms in Singapore, synthesizing the critical insights gained throughout the thesis.

2. Literature Review

This literature review comprises several sections that cover various aspects of Building Information Modeling (BIM). In Section 2.1, the introduction provides an overview of BIM. Section 2.2 explores different frameworks for assessing BIM maturity. The implementation of BIM in Singapore is discussed in Section 2.3. Furthermore, Section 2.4 focuses on the relevant actors involved in BIM. The barriers and drivers associated with BIM implementation are addressed in Sections 2.5 and 2.6 respectively. Finally, Section 2.7 delves into the interventions discussed in the literature.

2.1. BIM

2.1.1. Definition of BIM

Building Information Modeling (BIM) has revolutionized the architecture, engineering, and construction industry by introducing a digital approach to design, construction, and facility management. The concept of BIM has its roots in the 1970s, as documented by the Institute of Physical Planning at Carnegie-Mellon University (Eastman et al., 2011). However, it wasn't until the early 2000s that the term "Building Information Modeling" gained widespread popularity. Various terminologies such as "Virtual Buildings," "Integrated Project Models," and "Virtual Design and Construction" were used to describe digital representations of the building process (Eastman et al., 2011). The term "Building Information Modeling" was first introduced by Van Nederveen and Tolman in 1992, providing a more standardized label for the digital representation of buildings. The literal meaning of the term "Building Information Modeling" and its alternatives has been a subject of debate among industry professionals, writers, and academics. Some argue that the mere presence of a label or acronym does not necessarily enhance understanding, while others see it as vital for effective communication and semantics (Santini, 2002). Numerous attempts have been made to differentiate between the various terms, but the significant overlaps in their meanings question the uniqueness of individual terms (Lee et al., 2005).

The literature on BIM does not present a single, universally accepted definition. Abbasnejad and Moud (2013) examined the challenges associated with BIM, including its definition and interpretations, and found a wide variety and frequency of BIM definitions. This diversity of definitions highlights the confusion surrounding BIM and the need for precision when discussing the concept. While proposing a unique definition is challenging, researchers have emphasized the inclusion of key characteristics in defining BIM (Abbasnejad & Moud, 2013; Suermann & Issa, 2009). To capture the essential aspects of BIM, several studies have proposed definitions that highlight its core features. For instance, Succar (2009) defines BIM as "a set of interacting policies, processes, and technologies generating a methodology to manage essential building design and project data in a digital format throughout the building's life-cycle." This definition emphasizes the integration of policies, processes, technologies to manage building information digitally. Another definition by Sander Van Nederveen et al. (2010) describes BIM as "an information model of a building (or building project) that comprises complete and sufficient information to support all lifecycle processes." It emphasizes that BIM should include information about the building itself, its components, and properties, enabling computer applications to interpret it for various lifecycle processes.

The US National BIM Standard Committee (NBIMS) definition, adopted by the author for this thesis, highlights BIM as a "digital representation of physical and functional characteristics of a facility" (virtual representation). It also emphasizes its role as an "information repository" that serves as a shared knowledge resource for informed decision-making throughout the facility's lifecycle (NBIMS).

2.1.2. BIM Dimensions

Building Information Modeling (BIM) encompasses multiple dimensions that extend beyond the traditional 3D representation of objects. Eastman et al. (2011) used the term 'nD' modeling to describe BIM's multidimensional capability, which allows for the inclusion of numerous dimensions into the model.

In the context of Singapore, the Building and Construction Authority (2017) provides a comprehensive definition of BIM dimensions:

- 3D Dimension: This dimension involves spatial information, including geometric and material data of objects. It facilitates clash detection and coordination, fabrication, visualization, and various applications such as simulations, systems coordination, virtual reviews, and site utilization studies.
- 4D Dimension: Building upon the 3D model, the fourth dimension incorporates time-related information. It enables virtual design and construction (VDC) services involving temporary analyses like sequencing, scheduling, progress tracking, and simulation of construction or installation sequences. It supports sequencing, scheduling, simulation of construction or installation sequences progress tracking, project phasing simulations, and visual validation for payment approval.
- 5D Dimension: The fifth dimension combines the 3D model with cost-related data. It supports VDC services involving cost and resource planning, cost estimates, and progress billing. It enables activities such as value engineering, what-if scenarios, and quantity extraction to support detailed cost estimates.
- 6D Dimension: Going beyond design and construction, the sixth dimension incorporates operation and management data suitable for facility managers. It includes information such as maintenance manuals, specifications, and warranties. The 6D dimension supports life cycle BIM strategies, BIM-embedded quality and maintenance (Q&M) manuals, and BIM-based maintenance and technical support.

2.2. BIM in Singapore

This section presents a literature review focused on the revolutionary project delivery processes involving the implementation of Building Information Modeling (BIM) in the construction industry. It explores the journey from BIM project delivery process to Virtual Design and Construction (VDC) and Integrated Digital Delivery (IDD). The literature review summarizes the key activities associated with BIM in these processes and provides a comprehensive comparison among them.

2.2.1. BIM project delivery process

Building Information Modeling (BIM) is a collaborative process that facilitates the exchange of information among various stakeholders in a construction project, including architects,

engineers, contractors, consultants, and clients. BIM allows for the generation and analysis of diverse views, data, and information tailored to meet the needs of different users. This capability enhances decision-making and streamlines the facility delivery process. Implementing BIM can lead to productivity improvements by minimizing disruptions in information flow during design and construction stages, facilitating effective response to changes, promoting communication and collaboration among stakeholders, aiding informed decision-making, enabling information sharing and interoperability, and reducing changes, workload, and costs. By reducing manual efforts, time, and expenses involved in onsite operations, BIM also enhances project performance, enabling practitioners to effectively control schedule, budget, quality, and mitigate risks.

Recognizing the potential of BIM, the Singapore government has been actively promoting its use in the construction industry as a critical tool for enhancing national productivity. The Building and Construction Authority (BCA) launched the BIM Roadmap in 2010 with the goal of achieving 80% adoption of BIM in the construction industry by 2015. This initiative is part of a broader plan to improve the industry's productivity by 25% over the next decade (BCA, 2011). To prepare the industry for BIM implementation, the BCA introduced various initiatives following the BIM Roadmap. In 2011, the National BIM Steering Committee, comprising representatives from professional institutions, trade associations, government procurement entities, and regulatory agencies, was established to govern the implementation of the BIM Roadmap (BCA, 2013). The committee spearheaded the development of the "Singapore BIM Guide" and "BIM Particular Conditions." These efforts resulted in a significant increase in BIM adoption rates, rising from 20% in 2009 to 65% in 2014. Singapore has emerged as a leader in BIM implementation in Asia, evidenced by the issuance of 12 out of 35 BIM standards in the region (Cheng & Lu, 2015).

2.2.2. Virtual Design and Construction

Virtual Design and Construction (VDC) was introduced by Singapore's Building and Construction Authority (BCA) in 2015. According to Chua and Yeoh (2015), VDC is an approach that promotes collaboration between designers and contractors as a team to build, visualize, analyze, and evaluate project performance using multidisciplinary models in the design stage. This allows for thorough assessment before significant time and resources are invested in construction. The BCA defines VDC as the management of both BIM models and the people and processes involved, aiming to achieve specific project or organizational goals and improve overall performance.

VDC essentially involves "Building Twice": first virtually and then physically. Project teams can identify potential issues and make necessary adjustments before implementing them on-site by simulating design and construction activities in a virtual environment. This framework requires all stakeholders to commit to collaborative work towards shared goals. It involves systematically modeling, rehearsing, and building based on the virtual representation, while continuously measuring and minimizing deviations between the virtual and physical outcomes. VDC consists of four stages: design, construction coordination, virtual planning, and execution. BIM is one VDC component, functioning as a comprehensive database that integrates all the information required for specific activities within the virtual model. The VDC

framework addresses three gaps in the BIM project delivery process: limited development of BIM beyond regulatory submission during the design phase, significant time spent resolving design-intent discrepancies, and underutilization of BIM during construction. VDC is designed to support a multidisciplinary project team, involving stakeholders such as architects, engineers, contractors, owner representatives, and suppliers from the early design stage. This ensures well-informed inputs to the design process (BCA, 2017).

Li et al. (2009) presented eight advantages of VDC, including the stimulation of innovative design, detection of design errors, rehearsal and optimization of construction plans, identification of unsafe areas, effective construction site management, improved communication, enhanced project information and knowledge management, and reduction of managerial issues.

2.2.3. Integrated Digital Delivery

Integrated Digital Delivery (IDD) is a project delivery approach introduced by Singapore's Building and Construction Authority (BCA) in October 2017. It aims to digitally integrate work processes and stakeholders throughout the entire building lifecycle using digital technologies, with Building Information Modelling (BIM) as its core supporting technology. IDD comprises four phases: Digital Design, Digital Manufacturing and Fabrication, Digital Construction, and Digital Asset Delivery and Management, covering the entire lifecycle of a building project. In the Digital Design phase, stakeholders collaborate to achieve optimized and coordinated designs that meet client, regulatory, and downstream requirements. The Digital Manufacturing and Fabrication phase focuses on automating construction processes by translating designs into standardized components for off-site production. During the Digital Construction phase, technologies are employed to enhance operational efficiency at the project site. Real-time monitoring and control are utilized to maximize productivity, minimize rework, and enable just-in-time delivery, installation, and monitoring of on-site activities. In the Digital Asset Delivery and Management phase, technologies are adopted for real-time monitoring of building operations and maintenance. This phase aims to enhance asset values by ensuring efficient ongoing management and maintenance of the constructed facility (BCA, 2018).

The primary goal of IDD is to streamline coordination processes and enhance collaboration among stakeholders by integrating their work processes throughout the project lifecycle. IDD improves costs, schedule, and quality performance by improving information transfer and minimizing delays, duplications, and rework. Real-time monitoring, better site planning, and coordination enabled by IDD also contribute to improved on-site safety. These improvements ultimately lead to enhanced construction efficiency and productivity (BCA, 2018).

Since its launch in 2017, IDD is still in the early stages of implementation in the Singapore construction industry. To encourage digitalization, BCA has introduced a plan that provides training, digital platforms, and pilot projects for the industry. A survey by Hwang et al. (2020) explored IDD implementation and its perceived impact on project performance. The results indicated that 38.71% of organizations implemented digital technologies across all four phases of IDD.

2.2.4. Summary of Project Delivery Processes

The three project delivery processes, namely BIM, VDC, and IDD, exhibit an evolutionary trend that aims to enhance productivity, reduce rework, minimize wastage, and improve construction safety in the construction industry. While their objectives align, each process builds upon the previous one to bridge gaps or expand the use of BIM technologies and integrated workflows.

BIM is at the core of these processes, which serves as the digital representation of a building with geometric and semantic information of its components. It acts as a shared information platform throughout the building lifecycle, providing a comprehensive database for decision-making. BIM is considered the "Single Source of Truth" as it integrates all the necessary information required for specific activities within a virtual model.

In the next layer, VDC leverages BIM models to enhance communication during the design and construction phases. It utilizes BIM to facilitate collaboration, achieve project goals, and improve overall performance.

IDD, building upon VDC and BIM, extends its scope to cover the entire life cycle of a building. It adopts BIM as its core and integrates digitalization and technologies throughout the project lifecycle, spanning design, construction, fabrication, asset delivery, and management.

In summary, BIM forms the core foundation for VDC and IDD, with each component covering different project phases. The evolution of these processes demonstrates a progression towards the comprehensive integration of digital technologies and workflows to optimize the Singapore construction industry.

2.3. BIM Maturity Level Assessments

Building Information Modeling (BIM) has become increasingly popular in the construction industry, offering numerous benefits in terms of project coordination, collaboration, and efficiency. However, organizations need to assess and understand their current BIM maturity to fully leverage these advantages and improve project performance. This section will discuss the importance of measuring BIM maturity, the various BIM maturity models available, and their strengths, weaknesses, and applicability.

2.3.1. BIM Maturity Level Assessments

Building Information Modeling (BIM) has become increasingly popular in the construction industry, offering numerous benefits in terms of project coordination, collaboration, and efficiency. However, organizations need to assess and understand their current BIM maturity to fully leverage these advantages and improve project performance. This section will delve into the importance of measuring BIM maturity, the various BIM maturity models available, and their strengths, weaknesses, and applicability.

Assessing BIM maturity is crucial for organizations as it allows them to identify their current level of capability and understand the extent of benefits they can expect from using BIM. Succar et al. (2012) argue that assessing BIM maturity improves productivity gains resulting from BIM implementation. By measuring BIM maturity, organizations can justify the significant capital and time investments made in adopting BIM (Mansson et al., 2017). To

measure BIM maturity effectively, organizations must consider the differences in scale due to diverse markets, disciplines, and organization sizes. Different BIM maturity models have been introduced to address these variations in the construction industry context (Smits et al., 2017). Some models, such as the BIM Scorecard and NBIMS' ICMM, focus on assessing BIM within specific projects, while others like BIMCAT and BIM QuickScan target evaluating the maturity of organizations (Dakhil et al., 2015).

Succar's BIM Maturity Index (BMI) was one of the first models developed to assess BIM maturity (Succar, 2009). It consists of three fields: policy, process, and technology, with five distinct maturity levels: initial/ad-hoc, defined, managed, integrated, and optimized. While the BMI provides a blueprint for future BIM capability maturity, its components are poorly defined, resulting in rough estimates in measurement results.

The BIM QuickScan, launched by the Netherlands Organisation for Applied Scientific Research (TNO) in 2009, is another widely used BIMMM (Sebastian & Van Berlo, 2010). It comprises four chapters: organization and management, mentality and culture, information structure, and tools and applications. The BIM QuickScan incorporates both organizational and technological aspects of BIM performance and offers five maturity levels: initial/adhoc; managed; defined; measured; and optimised. However, it lacks methods and procedures for identifying the chapters, making it challenging to convince BIM users that the assessment results reflect their actual BIM maturity.

Mom and Hsieh (2012) developed a BIM maturity model that focuses on assessing BIM technology implementation at the organizational level. Their framework includes six levels of BIM maturity: incomplete, performed, managed, defined, quantitatively managed, and optimizing. While this model provides key factors for assessing BIM implementation, it heavily relies on existing maturity models and may require frequent updating to address the latest practical issues in BIM.

Liang et al. (2016) introduced the Multi-scale BIM Maturity Model (MBMM), which organizes the domains of technology, process, and protocol in a hierarchical pyramid. It employs detailed rubrics that facilitate the assessment of each subdomain, with assessment results indicating a specific stage ranging from 0 to 3. These rubrics consist of evaluative criteria, quality definitions for the criteria at different levels of achievement, and a scoring strategy that allows for presentation and assessment in a table format. One notable feature of the MBMM is its ability to measure BIM maturity across different scales, from individual projects to an organization's entire project portfolio. It effectively condenses the BIM maturity stages of various projects and provides an overview of the organization's overall BIM maturity. Furthermore, the MBMM enables analysis at the national economy level. However, a limitation of this method is the challenge in interpreting the results since it does not provide a single overall score indicating the organization's BIM maturity.

Siebelink (2017) introduced a BIM maturity model that consists of six categories and six level of BIM maturity level. The first category, strategy, focuses on elements such as BIM vision, goals, management support, and BIM expertise. The second category, organizational structure, includes tasks, responsibilities, and contractual aspects within the organization. The

third category, people and culture, takes into consideration factors like personal motivation, the presence of a requesting actor, education, training, support, cooperation, openness, and transparency. BIM processes, including procedures and process change, fall under the fourth category. The fifth category, ICT, incorporates hardware, software, and BIM facilities. Finally, the sixth category, data, addresses aspects such as information and object structure, the object library, and data exchange. The six level of maturity consists of not present, initial, managed, defined, quantitatively managed, and optimized. Siebelink's model has been tested and proven to accurately describe the execution of different maturity levels in practice. By considering these six categories, the model provides a comprehensive framework for assessing and measuring BIM maturity within an organization.

In the evolution of BIM maturity models (BIMMMs), there has been a shift from initially focusing solely on the technological aspects of BIM to incorporating organizational and human elements as well. BIMMMs are designed with their own specific categories for assessing maturity levels. Each BIMMM employs a unique set of elements tailored to the specific target users. These elements can be grouped into five categories: organizational, IT infrastructure, people, process/procedures, and information/data (Siebelink, et al., 2018).

The maturity levels in BIMMMs typically follow a similar structure, using well-accepted descriptors. The lowest or first level on the maturity spectrum is often described as initial/ad hoc or not present, indicating the absence of defined BIM processes. The widely recognized number of maturity levels in BIMMMs is five, aligning with the levels defined in the Capability Maturity Model Integration (CMMI) introduced by Paulk et al. (1993). These levels include initial, repeatable, managed, defined, and optimizing stages. Table 2.1 provides an overview of the BIMMMs in study.

Table 2.1: The characteristics of BIM Maturity models

BIM Maturity Model	Factors included	Maturity Levels	Applicability
(Succar, 2009)	policy, process, and technology	initial/ad-hoc, defined, managed, integrated, and optimized	Organization
(Sebastian & Van Berlo, 2010)	organization and management, mentality and culture, information structure, tools and applications	initial/adhoc, managed, defined, measured, and optimized	Organization
(Mom & Hsieh, 2012)	process, organizations, applications, tools, project teams and business models	incomplete, performed, managed, defined, quantitatively managed, and optimizing	Organization
(Liang, et al., 2016)	technology, process, protocol	Stage 0, stage 1, stage 2, stage 3	Project, Organization, Industry
(Siebelink, 2017)	strategy, organizational structure, people and culture, BIM processes, ICT (infrastructure) and data (structure)	not present, initial, managed, defined, quantitatively managed, and optimized	Organization

2.3.2. BIM Maturity Assessment in Singapore

Currently, there is no established BIM maturity assessment framework specifically developed for the Singapore market. Instead, the evaluation of BIM performance for projects or organizations in Singapore relies on a set of Key Performance Indicators (KPIs) defined by the project team or company management (BCA, 2013). These KPIs serve as a means to assess BIM adoption and effectiveness.

At the project level, the following KPIs are commonly considered: the percentage of projects conducted using BIM, the involvement of project partners in BIM, the extent of BIM implementation across project stages, the number of additional services offered through BIM, the accuracy of BIM deliverables, and the reduction in time delay and cost overrun through BIM implementation.

At the organization level, the KPIs focus on the extent of BIM adoption programs implemented and comprises categories such as leadership, planning and results, information and process, people and capability, customer engagement, and new ways of working.

For employee capability assessment, KPIs include the percentage of employees trained and certified in BIM, the level of BIM skills acquired (including planning, authoring, analysis, collaboration, documentation, and customization), the percentage of BIM skills applied in projects, and the percentage of employees trained in specific BIM roles such as BIM Managers, BIM Coordinators, and BIM Modelers.

Each KPI can be measured in terms of output, outcome, and impact. For example, the input of training resources can be assessed by the output of the number of staff trained, the outcome of the extent of project stages conducted in BIM, and the impact of the organization's ability to secure BIM project contracts.

It's important to note that the Building Control Authority of Singapore does not mandate a specific set of KPIs but provides them as examples in their BIM guide. As a result, there is currently no unified and standardized method to determine the BIM maturity level of organizations in Singapore. Evaluation relies on the adoption of relevant KPIs and the measurement of BIM-related outcomes and impacts to assess the effectiveness of BIM implementation.

2.4. BIM Actors

Building Information Modeling (BIM) has brought significant changes to the construction industry, necessitating the development of new resources and capabilities within organizations. This has led to the emergence of formal and informal BIM-specialist roles across various aspects of architecture, engineering, and construction (AEC), ranging from design and project management to operations and maintenance. To support successful BIM implementation, many countries, industry bodies, research coalitions, and organizations have introduced guides and standards that define key roles required for effective BIM practice.

2.4.1. BIM Actors

Different studies have explored various BIM roles, with some distinguishing between roles such as BIM managers, BIM coordinators, and BIM modellers (Davies et al., 2017). However,

there is also a recognition that the distinction between these roles can be blurry, as they often involve similar responsibilities. In a study conducted by Uhm et al. (2017), an analysis of job postings revealed 35 distinct job types characterized by overlapping descriptions and requirements. These job types can be categorized as project roles, primarily performed within project teams, and organizational roles, primarily carried out at the company level. One study by Bosdriesz (2018) specifically focused on the organizational level of BIM implementation. The study distinguished between intra-organizational actors at the group and user levels. The group level included relevant firms and departments involved in the building process, while the user level includes non-technical and technical users. Non-technical users are stakeholders who work with the data available in the BIM model without needing to understand all the complexities, while technical users are experts responsible for creating the model and adding initial data.

BIM actors have emerged as crucial contributors to the advancement and development of BIM. They play a significant role in promoting and diffusing the use of BIM within project networks and across organizational boundaries. BIM actors advocate for the value and acceptance of the technology, develop practices for its use, and negotiate and adapt to existing workflows in construction project management (Kokkonen & Alin, 2016). They are instrumental in diffusing BIM management through activities such as promotion, training, information dissemination, and the development of new practices and educational programs within construction projects (Bosch-Sijtsema & Gluch, 2021).

The role of the BIM actor serves as an interface between technology and its users, bridging the gap between the virtual object and human actors. They facilitate change in current processes through the use of technology. This role requires not only technological capabilities with BIM tools but also contractual and financial knowledge to enforce a coordinated process. The BIM specialist must possess leadership, communication, and documentation skills, as well as proficiency in model authoring and coordination software. They facilitate a collaborative approach by enforcing coordinated processes and mitigating individualistic approaches. The ability to lead, communicate, write documentation, and implement quality assurance procedures is essential for BIM specialists beyond their technical proficiency. While technological skills are now becoming less of a barrier with the widespread adoption of BIM, attention must be given to process-focused and collaboration aspects when defining roles and skills (Davies et al., 2017).

2.4.2. BIM Actors in Singapore construction industry

Building Control Authority (BCA) in Singapore has developed guidelines to categorize the actors involved in the Building Information Modeling (BIM) process. These guidelines provide clarity on the roles and responsibilities of various stakeholders in modeling, BIM implementation within organizations, and effective BIM collaboration.

When it comes to modeling, two key actors can be identified: the model author and the model user. The model author is responsible for creating and maintaining a specific model according to the prescribed level of detail outlined in the BIM execution plan. On the other hand, model users are authorized parties who can access and utilize the model for the project. The model

can be provided in native or neutral formats, such as IFC, for the reference and use of model users (BCA, 2013).

In terms of BIM implementation within organizations, the BCA recognizes four key actors with distinct roles and responsibilities. These actors are the senior corporate leaders, organization BIM managers, BIM specialists, and BIM modelers. Senior corporate leaders take the lead in the organization's BIM Committee and adoption program. They manage the progress of the adoption program and provide necessary resources for its implementation. Organization BIM managers are responsible for identifying BIM opportunities in key business processes, conducting pilot projects, evaluating results, incorporating BIM into key processes, establishing and maintaining BIM standards, identifying suitable BIM technology/software, and developing BIM training programs based on the organization's needs. BIM specialists serve as key resource persons in BIM. They provide mentoring to project BIM teams, consolidate success stories to produce good practice guides, facilitate practice sharing workshops, and experiment and evaluate new practices, processes, and technology related to BIM. BIM modelers are responsible for the production and modification of discipline-specific information within the model. They must possess appropriate technological skills to effectively create and modify the model (BCA, 2013).

For effective BIM collaboration, the BCA emphasizes several principles. Active commitment from all stakeholders and project team members to their roles and responsibilities is crucial for successful BIM implementation. BIM should be the responsibility of the entire team, rather than a single department or person. Other team members may need training to utilize BIM models in their work processes and improve overall team integration (BCA, 2017).

The BCA identifies two types of BIM Collaboration team setups: project team stakeholders and organizational team stakeholders. Project team stakeholders include clients, consultants, and contractors. Clients are the main drivers of BIM among all project stakeholders and recognize the overall benefits of BIM to project and business objectives. Consultants recognize the benefits of BIM to their individual processes and workflows and collaborate and share information accordingly. Contractors manage information and issues from various stakeholders to develop constructible BIM and make the most of model information in construction.

On the other hand, organizational team stakeholders consist of management, commercial teams, and the centralized BIM team within the organization. Management plays a vital role in recognizing the overall benefits of BIM to corporate objectives and driving BIM implementation throughout the organization. Commercial teams acknowledge the benefits of BIM to individual processes and workflows and integrate BIM where feasible. The centralized BIM team provides technical and skills support to commercial groups within the organization through various resource and mechanism such as in-house training, individual training plans, knowledge sharing, BIM content libraries, BIM templates, implementation guidelines, corporate standards, audit checklists, BIM modeling guides, technical support, handholding, research and innovation initiatives, and technological solutions.

The BCA envisions organizations to undergo necessary restructuring and integrate roles and workflows. Currently, the practice involves a BIM coordinator acting as an intermediary to extract information from the model as needed by other project team members. However, in the future, a centralized BIM team will provide skills and technical support to help project team members effectively utilize the data in the BIM model for their specific tasks. Presently, "BIM" is seen as a separate entity and role from the designer or coordinator, leading to a knowledge gap between domains. In the future, the vision is for a unified entity that combines both BIM and design/technical knowledge, utilizing BIM to perform design and coordination functions (BCA, 2017).

The approach taken by the Building Control Authority (BCA) in Singapore aligns with the findings from various literature sources. It recognizes that BIM actors includes not only professional BIM roles, but also other stakeholders involved in the project and organization who utilize information from the model. BIM is considered a collective responsibility of the entire team, rather than the sole responsibility of a specific firm, department or individual. The distinction between project BIM actors and organization BIM actors exists, but their roles are interconnected and mutually supportive for the successful implementation of BIM in both environments. Last but not least, the BCA acknowledges the need for BIM actors to possess not only technical skills but also leadership, communication, documentation, and software proficiency to effectively carry out their responsibilities.

2.5. BIM Barriers

The implementation of Building Information Modeling (BIM) in the construction industry is accompanied by various barriers that can hinder its successful adoption and integration. This section provides a comprehensive overview of these barriers, categorized into four groups: resistance to new technology, lack of knowledge and experience, issues regarding software and hardware, and the absence of a BIM implementation framework. The summary of 19 barriers to BIM implementation in organizations, derived from a literature review of 11 previous studies, is presented in Table 2.2

One significant barrier to BIM implementation is the conservatism and resistance to change within the Architecture, Engineering, and Construction (AEC) industry. Professionals comfortable with established workflows may be hesitant to embrace BIM due to concerns about increased complexity and disruption to existing practices. This resistance can impede adopting and effectively utilizing BIM technologies and processes. Another barrier to BIM implementation is getting stakeholders to agree on protocols and standards for information exchange. Without standardized processes, organizations face difficulties in integrating BIM across multiple disciplines and at the construction level, leading to communication gaps and potential conflicts. Effective collaboration and information sharing among project participants are vital in BIM. However, differences in data formats, software platforms, and interoperability standards often impede seamless information exchange. Another barrier is the lack of understanding by executives about the value of BIM processes. Executives and decision-makers within organizations may not comprehensively understand the benefits BIM can bring, such as improved collaboration, reduced rework, and enhanced project outcomes. This lack of awareness can result in a reluctance to invest in BIM or allocate resources for its

implementation. Decision-makers may be hesitant to invest in BIM without tangible evidence of its positive impact on project outcomes and return on investment. Implementing BIM often requires changes in corporate culture and structure, which can be met with resistance. Furthermore, the lack of sufficient evidence supporting the benefits of BIM can act as a barrier. The upfront costs associated with BIM implementation, including hardware, software, training, and integration, can act as a barrier, particularly for organizations with limited financial resources. If the perceived costs outweigh the expected financial benefits, decision-makers may hesitate to invest in BIM. Additionally, firms may be reluctant to invest in training programs due to concerns about costs and potential productivity loss during the learning curve. Even after providing training, some individuals may continue to resist using new technology such as BIM. This reluctance can be attributed to various factors, including a lack of confidence in using the technology, complexity of the software, or a preference for traditional methods.

The barriers related to a lack of knowledge and experience in BIM implementation can significantly hinder the adoption of this technology in the construction industry. One significant barrier is the shortage of skilled employees in BIM. This shortage makes it challenging for organizations to implement BIM effectively and efficiently. Another barrier is the lack of practical, on-the-job knowledge among BIM operators. While individuals may have theoretical knowledge of BIM, they may lack hands-on experience in construction process and technology. This gap between theoretical knowledge and practical application can hinder the successful adoption of BIM. Furthermore, there is a lack of relevant BIM expertise and experience within the industry. Many professionals may not have direct exposure to BIM practices or projects, limiting their ability to contribute effectively to BIM implementation. This lack of expertise can delay the adoption and integration of BIM into construction projects. In addition, a lack of knowledge in BIM standards and technologies poses a barrier. BIM involves the use of specific standards, protocols, and software tools. Professionals may struggle to implement BIM effectively and align their practices with industry requirements without adequate knowledge of these standards and technologies. Field staff's dislike of BIM coordination meetings also presents a barrier to implementation. Field staff, who are responsible for on-site construction activities, may perceive BIM coordination meetings as time-consuming and unnecessary, leading to resistance and reduced participation.

The implementation of BIM in the construction industry faces various barriers related to software and hardware. One significant barrier is the high costs associated with investing in BIM hardware and software. Implementing BIM requires organizations to acquire and maintain specialized hardware and software tools, which can be financially burdensome, especially for small and medium-sized enterprises. The cost factor may discourage some organizations from adopting BIM or limit their ability to invest in the necessary resources. Technical challenges with multi-disciplinary integration and multi-user access to models also pose barriers to BIM implementation. BIM involves the collaboration of various disciplines and stakeholders, each contributing their expertise to the project. However, integrating the different models and ensuring seamless collaboration among multiple users can be technically complex. Challenges may arise in terms of model compatibility, data exchange, and coordination, hindering the effective implementation of BIM. Interoperability issues due to

software selection and insufficient standards further impede BIM implementation. Different software tools and platforms may have compatibility issues, making it difficult to exchange data between systems. Inadequate standards and protocols for data exchange can lead to inconsistencies and inefficiencies in BIM workflows. The complexities of implementing BIM technologies into projects present another barrier. BIM implementation involves changes in workflows, processes, and project management approaches. Adapting to these changes and ensuring a smooth transition from traditional practices to BIM can be a complex endeavor. The increasing need for specialized software and lack of domestic-oriented BIM tools is also a barrier to BIM implementation. As BIM evolves and becomes more sophisticated, specialized software tools is required to cater to specific project requirements or adapt to local work process. However, these specialized tools often come with a learning curve and require additional training and investment. The need to keep up with the evolving software landscape and select the most appropriate tools for specific project needs can pose challenges to organizations implementing BIM

Without a clear framework, organizations face difficulties in integrating BIM across multiple disciplines and at the construction level. The lack of standardized processes and guidelines hampers the seamless collaboration and coordination required in BIM projects. Difficulties in multi-disciplinary and construction-level integration arise due to the absence of a structured framework that outlines the roles, responsibilities, and workflows of different stakeholders involved in BIM projects. Without a framework in place, it becomes challenging to align the efforts of architects, engineers, contractors, and other professionals involved in the project, leading to communication gaps and potential conflicts. Furthermore, the lack of building standards and regulations for BIM poses a barrier to its implementation. Building codes and regulations often lag behind the rapid advancement of BIM technology. The absence of clear guidelines and mandates regarding BIM usage in the construction industry hinders its widespread adoption and limits its potential benefits.

Table 2.2: Barriers to BIM Implementation

Group of barriers	Barriers	1	2	3	4	5	6	7	8	9	10	11
Resistance to new technology	Difficulty in achieving consensus among key stakeholders regarding the exchange of information.	x			x	x					x	
	The industry's resistance to change and tendency to maintain traditional practices.			x		x	x	x	x	x		x
	Executives' limited understanding of the value and benefits of BIM processes.		x	x			x			x		x
	Insufficient empirical evidence supporting the advantages of implementing BIM.			x			x	x	x	x		x
	Continued reluctance to adopt new technologies, even after training and education.						x	x				x
	The costs associated with implementing and maintaining BIM outweighing the financial benefits.	x	x	x			x		x			
	Firms' hesitancy to invest in training due to concerns about expenses and potential decreases in productivity.		x		x		x		x			
Lack of knowledge and experience	Shortage of skilled employees proficient in BIM methodologies.	x	x	x	x	x	x		x	x	x	x
	BIM modelers lacking practical knowledge and experience.			x						x	x	
	Limited availability of qualified professionals with relevant expertise in BIM standards and technologies.		x			x	x					x
	Disinterest among field staff in attending BIM coordination meetings.					x					x	
Issues regarding software and hardware	High expenses related to procuring BIM hardware and software.	x	x				x		x	x		x
	Technical challenges involved in integrating multiple disciplines and enabling multi-user access to BIM models.				x		x					
	Interoperability problems caused by software selection and insufficient standardization.	x			x			x				x
	Complexities associated with implementing BIM technologies in projects.					x				x		x
	Growing demand for specialized software in the BIM and lack of domestic-oriented BIM tools			x	x		x			x		x
Lack of BIM implementation framework	Difficulties in integrating multiple disciplines and construction-related aspects.				x				x			
	Lack of established building standards and regulations specifically for BIM implementation.			x		x	x					x

(1: Aranda-Mena, et al., 2009; 2: Bernstein et al., 2012; 3: Tan et al., 2019; 4: Eastman et al., 2011; 5: Forsythe et al., 2015; 6: Juan et al., 2017; 7: Kent & Becerik-Gerber, 2010; 8: Khosrowshahi & Arayici, 2012; 9: Kiani, et al., 2015; 10: Turk, 2016; 11: Zahrizan, et al., 2013)

2.6. BIM Drivers

Apart from the obstacles, there are also factors that motivate the implementation of BIM. This research has identified a total of 14 driving factors for full BIM implementation from 11 previous studies conducted in different countries. These factors are categorized into three groups: government support, promotion of collaboration within the organization, and improvement of design and construction quality. Table 2.3 provides a list of the identified drivers and the number of times they have been studied by different references.

The support from the government plays a pivotal role in the successful implementation of Building Information Modeling (BIM) practices. This support consists of various drivers that contribute to the widespread adoption of BIM across industries. Firstly, governments often provide subsidies for training, software, and consultancy costs associated with BIM implementation. These financial incentives encourage organizations to invest in BIM technology, making it more accessible and affordable for businesses of all sizes. Secondly, effective governance of BIM-related policies, standards, and guidelines is a crucial driver. Governments establish frameworks that outline the requirements and expectations for BIM implementation, ensuring consistency and interoperability across projects. This effort helps streamline processes, enhance collaboration, and mitigate risks associated with new construction practices. Additionally, early participation in BIM use by government agencies fosters its acceptance and adoption. Early adoption by government agency set an example for the industry and inspire other stakeholders to follow suit.

Promoting collaboration within an organization is also a critical driver for successful implementation of Building Information Modeling (BIM). This collaborative approach fosters an environment where teams can work together seamlessly and share information effectively. Several drivers contribute to the promotion of collaboration in BIM implementation. Firstly, organizations recognize the competitive advantages gained from successful BIM use. BIM enables improved project coordination, reduced errors, enhanced visualization, and streamlined communication among project stakeholders. These benefits incentivize organizations to prioritize collaboration to achieve higher project efficiency, cost savings, and client satisfaction. Another driver is the requirement for all disciplines to work together and share models. BIM encourages a multidisciplinary approach, where architects, engineers, contractors, and other professionals collaborate closely from the project's inception to completion. BIM implementation often requiress changes in organizational structure and culture. This includes breaking down silos and fostering a culture of collaboration and knowledge sharing. By redefining roles and responsibilities, organizations can create cross-functional teams that collaborate effectively, exchange insights, and collectively work towards project success.

BIM technology offers a range of features and capabilities that contribute to achieving higher levels of quality throughout the project lifecycle. BIM allows different disciplines, such as architecture, structural engineering, and MEP systems, to collaborate and detect clashes or conflicts early in the design phase. Resolving these clashes upfront can minimize potential construction issues and rework, leading to improved design quality. Complex design analysis is another driver. With BIM, sustainability analysis and constructability assessments can be performed more comprehensively and accurately. These analysis result in higher-quality designs that align with sustainability goals and optimize constructability. BIM 3D visualization capabilities enhance design communication. By creating realistic, three-dimensional visualizations of the project, stakeholders can better understand and visualize the design intent. This improves communication among project participants, enabling clearer

discussions, feedback, and decision-making. The visual representations facilitate a shared understanding of the project, improving design quality and reducing misunderstandings or errors.

BIM also allows for seamless updating of the model when design changes occur. It ensures that all project documentation, including drawings, schedules, and quantities, remains synchronized and accurate. By automating the drawing production process, BIM eliminates the risk of inconsistencies or errors that can arise from manual drafting, resulting in higher-quality documentation that aligns with the latest design revisions. BIM enables convenient production of models and drawings for construction and fabrication. By leveraging BIM data, construction and fabrication teams can generate detailed, accurate models and drawings that facilitate precise fabrication and assembly of building elements. The high accuracy of model-based documentation allows for precise measurements, quantities, and specifications to be embedded within the model. This data-rich documentation ensures that the design intent is accurately conveyed, reducing ambiguity and improving the quality of construction and fabrication processes. Four-dimensional (4D) simulation is another powerful driver enabled by BIM. By incorporating time as the fourth dimension, BIM facilitates the visualization and analysis of project schedules and construction sequences. 4D simulation allows project teams to identify potential schedule conflicts, optimize construction sequencing, and anticipate resource allocation. This enhances construction planning, minimizes delays, and improves overall project quality. BIM also enables more off-site fabrication and assembly of standard elements. By leveraging the accuracy and detail of BIM models, standard components can be prefabricated off-site, leading to improved quality control, reduced waste and manpower on-site, and increased construction efficiency.

Table 2.3: Drivers to BIM implementation

Group of drivers	Drivers	1	2	3	4	5	6	7	8	9	10	11
Support from government	Government financial incentive for firm and project implemented BIM						x					x
	Establishment of policies, standards, and guidelines to govern BIM-related practices.						x					x
	Government agencies take lead in adopting BIM technologies.	x										x
Promotion of collaboration within the organization	Attaining competitive advantages through successful implementation of BIM.			x			x					
	Collaboration and information sharing among different disciplines using shared models.		x			x		x	x	x	x	x
	Organizational structure and cultural changes as the result of adoption of BIM.						x					x
Improvement of design and construction quality	Coordination of design between disciplines through clash detection and resolution.	x	x	x	x	x	x	x	x	x	x	x
	Utilization of BIM for complex design analysis in sustainability and constructability.	x		x		x			x	x		x
	Enhanced design communication through 3D visualization.			x	x	x	x	x	x			
	Automatic updating of models and production of drawings to accommodate design changes.		x			x			x			
	Efficient generation of models and drawings for construction and fabrication purposes.	x	x	x		x	x			x		x
	High precision in generating model-based documentation.			x		x			x			
	4D simulation to visualize construction processes before they begin.	x		x	x	x			x	x	x	
	Facilitating off-site fabrication and assembly of standard components.				x	x		x		x	x	

(1: AIACC, 2014; 2: Chua & Yeoh, 2015; 3: Eastman et al., 2011; 4: Fischer, 2008; 5: Gao & Fischer, 2006; 6: Juan et al., 2017; 7: Khanzode & Reed, 2007; 8: Khosrowshahi & Arayici, 2012; 9: Kunz & Fischer, 2012; 10: McFarlane & Stehle, 2014; 11: Oo, 2014)

2.7. Intervention to Overcome BIM Barriers

Limited attention has been given to guidelines for addressing Building Information Modeling (BIM) barriers at the organizational level, with most contemporary studies focusing on strategies for enhancing BIM implementation at the project or industry level. However, the proper implementation of BIM has the potential to shift project management from an intra-firm level to inter-organizational cooperation, bringing significant advantages to the construction industry and leading to a paradigm shift (Zheng et al., 2017). Implementing BIM in a building project can be viewed as a gradual organizational evolution, as firms often find themselves in comfortable zones and need to embrace new technology and adapt to a new delivery process (Azhar et al., 2014). To address these challenges, this section first reviews literature on organization change theory, and then focuses on specific solutions aimed at overcoming barriers to BIM implementation. By understanding organizational change and implementing appropriate strategies, firms can effectively navigate the transition towards successful BIM adoption and reap the associated benefits.

2.7.1. Organization Change and Change Management

Organizational change is crucial for organizations aiming to succeed and thrive in a dynamic environment. It involves the deliberate introduction of new thinking, actions, or operational styles to adapt to the environment and improve performance (Pardo-del-Val et al., 2012), (Michel et al., 2013). Building Information Modeling (BIM) has emerged as a beneficial technology for building projects. The impact of adopting new technologies in organizations can be understood through conceptual models like the one constructed by Rockart and Scott Morton (1984). Their model identified two groups of factors: internal elements (such as technology, strategy, organizational structure and culture, management processes, and individuals and their roles) and external forces. Changes in internal elements require corresponding adjustments in other areas to maintain organizational effectiveness.

The Massachusetts Institute of Technology (MIT) framework, known as the MIT90s framework, further developed the understanding of organizational transformation during technology acquisition. It considers organizational culture as a vital dimension and recognizes its integral role in the organization, covering structure, processes, and individual roles. The MIT90s framework has been applied in cross-enterprise environments, where collaboration is essential. Verdecho et al. (2012) adapted the framework to conceptualize collaborative interenterprise contexts in the renewable energy sector. Their framework categorized influential factors into four groups: strategy, organizational structure, business processes and infrastructure, and culture. Strategy plays a significant role as it drives collaborative relationships among stakeholders, influenced by the need for competitiveness. The framework's application was validated through a case study in a renewable energy project.

The Building and Construction Authority (BCA) of Singapore recommends a change management framework for the implementation of Building Information Modeling (BIM) in organizations. This framework consists of three key phases: creating a climate for change, engaging and enabling the change, and implementing and sustaining the change (BCA, 2013).

In the first phase, which spans 3 to 6 months, it is crucial for the major stakeholders to recognize the need for change and break away from conservative cultural norms. This involves

defining the urgency for change, establishing a clear vision, goals, and program, understanding key risks and success factors, and formulating change strategies. The aim is to create an environment where the adoption of information-oriented project delivery becomes inevitable.

The second phase, lasting 6 to 12 months, focuses on engaging and enabling the change. The company management takes the lead in implementing BIM by providing training to staffs on using new software applications and redefining workflows. Constant in-house training should also be provided to help employees adapt to new policies, procedures, and operations. Short-term performance gains are emphasized to convince the leadership team that BIM implementation adds value, thereby justifying long-term investments.

The third phase, which spans 12 to 24 months and beyond, centers around implementing and sustaining the change. Propagation of BIM practices from project to project or team to team is encouraged, with the establishment of quick start templates and progression paths for teams to develop in-depth knowledge. Clear ownership and accountability, reward systems, and the incorporation of BIM practices into the organization's ISO processes are vital for making the change stick.

2.7.2. Overcoming barriers in BIM implementation

To overcome barriers in BIM implementation, a holistic approach is required that includes various strategies and solutions. Drawing from the referenced articles, the following key solutions can help address these barriers effectively (Table 2.4). The referenced articles provide insights into the importance of skilled professionals, the development of frameworks, effective communication, advanced planning, training, and research and development efforts

Acquisition of skilled BIM professionals: The importance of skilled professionals in BIM cannot be overstated. Hiring or engaging individuals with expertise in BIM technologies ensures that the implementation process is led by experienced personnel who can navigate technical challenges, provide guidance, and drive successful adoption within the organization (Blayse & Manley, 2004).

Establish a comprehensive BIM framework: Establishing a robust BIM framework designed to the organization's specific needs is crucial. This framework should define standards, guidelines, and procedures for BIM usage, promoting consistency, interoperability, and collaboration among project stakeholders. It serves as a roadmap for BIM implementation, ensuring that everyone is aligned and working towards common objectives (Blayse & Manley, 2004; Stewart, et al., 2004; Lunn & Stephenson, 2000; Smith, 2014) .

Enhancing stakeholder communication: Communication plays a pivotal role in BIM implementation. Establishing open and transparent communication channels among stakeholders, including clients, designers, contractors, and suppliers, facilitates a shared understanding of project requirements, objectives, and BIM processes. Regular meetings, workshops, and collaborative platforms promote effective information exchange and decision-making (Smith, 2014).

Conducting thorough project studies and analyses: Conducting thorough studies and analyses early in the project lifecycle helps identify potential challenges and opportunities related to BIM implementation. By understanding project requirements and complexities, organizations can develop specific strategies, anticipate obstacles, and allocate resources effectively. This proactive approach mitigates risks and ensures a smoother implementation process (Lunn & Stephenson, 2000).

Provide training sessions and resources: Comprehensive training programs are essential for successful BIM adoption. Offering training sessions for all project stakeholders, including management, designers, engineers, and contractors, ensures that everyone has the necessary skills and knowledge to utilize BIM effectively. Training should cover technical aspects of BIM tools and software, as well as non-technical skills such as collaboration, communication, and change management (Stewart et al., 2004; Smith, 2014).

Encourage research and development in BIM technologies: Encouraging research and development in BIM technologies drives innovation and facilitates the advancement of BIM implementation. Investing in R&D initiatives, collaborating with academic institutions, and fostering partnerships with technology providers can lead to the discovery of new tools, techniques, and best practices. This promotes continuous improvement and keeps organizations at the forefront of BIM innovation (Suprun & Stewart, 2015; Chan, et al., 2017).

Table 2.4: Overview of possible interventions

Group of barriers	Potential Solutions	(Stewart, et al., 2004)	(Blayse & Manley, 2004)	(Suprun & Stewart, 2015)	(Chan, et al., 2004)	(Lunn & Stephenson, 2000)	(Smits, et al., 2017)
Resistance to new technology	Enhancing stakeholder communication						x
	Conducting thorough project studies and analyses					x	
Lack of experience and knowledge	Acquisition of skilled BIM professionals		x				
	Provide training sessions and resources	x					x
Issue in hardware and software	Encourage research and development in BIM technologies			x	x		
Lack of BIM framework	Establish a comprehensive BIM framework	x	x			x	x

3. Methodology

Chapter 3 of the dissertation presents the research methodology employed to achieve the objectives outlined in Chapter 1. The methodology includes several sections. In Section 3.1, the research approach is discussed in a general sense. Following that, Section 3.2 and Section 3.3 provide a detailed explanation of a method used to assess the BIM maturity level of the organization and identify the key actors involved in the BIM process. The next sections, 3.4 and 3.5, elaborate on how interviews were conducted to uncover the barriers faced by the actors and propose potential interventions to overcome these challenges. Finally, Section 3.6 delves into the testing of the effectiveness of the different interventions using cooperative game theory.

3.1. Introduction

In this study, a Singapore-based general contractor was selected as the focus of research due to its central role in construction projects and its emphasis on collaboration across disciplines. The contractor's impressive track record of receiving awards from the Singapore Building and Construction Authority in key areas such as BIM, VDC, and IDD demonstrated its progressive approach to BIM implementation. By concentrating on this particular firm, a comprehensive and in-depth understanding of BIM operations across various departments could be achieved. Furthermore, the contractor's strong performance in terms of quality and safety indicated its overall effective management.

The research methodology began with a survey to assess the existing level of BIM implementation and an interview identify the key actors involved in the BIM process. This provided insights into the contractor's BIM capacities. Barriers to BIM implementation were then identified through interviews conducted with the significant actors identified in the literature review and interview. Based on the most common barriers identified, interventions were designed to address and overcome these challenges. Subsequently, game theory was employed to test the effectiveness of the different interventions. The objective was to identify the intervention that would yield the overall maximized payoff for the organization, taking into account the shared benefits and costs associated with each intervention. This approach allowed for determining the intervention that would provide the best return on investment.

A visual representation of the research methodology is presented in Figure 3.1, illustrating the sequential steps followed to achieve the research objectives.

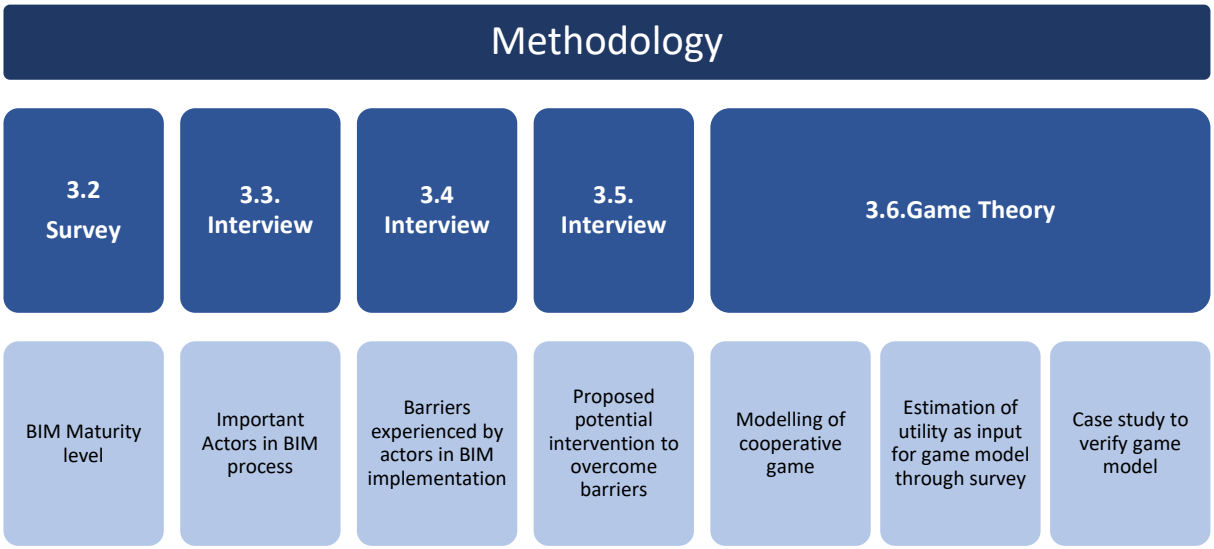


Figure 3.1: Overview of Research Methodology

3.2. Current BIM Maturity Level

There are many of data collection method that can be used in research. While the interview is effective in obtaining instant feedback and in-depth opinions, the survey has advantage in providing greater geographical distribution in which the result could be generalized. The aim of the survey is to gather quantifiable data of BIM capabilities level of the company, or in other word, BIM maturity level of the company

The survey in form of structured questionnaire was disseminated to the employee of the company via email. The respondent could access the survey by clinking to the attached link inside the email. The electronic survey is adopted for it advantages in giving flexibility for respondent to think and response the survey at their own pace and leisure. As the survey was sent out individually for selected respondent, it also ensured anonymity and privacy of respondent. A total of 51 survey sent out, 35 were replied. A copy of this survey can be found in Appendix A

The framework to determine BIM capabilities of the contractor firm is based on the framework proposed by Siebelink (2017) because of 3 reasons. Firstly, it is currently the most well-rounded framework, considering not only technology and process side but also human aspect in BIM adoption, an equally important aspect (Liu et al., 2017). Secondly, existing BIM maturity models have overlooked the varying levels of analysis. BIM can mature differently at the project, company, and industry levels, with different extents of adoption among companies (Liang et al., 2016). Thirdly, there is currently no comparable framework developed for Singapore construction industry. The latest development in term of evaluation framework for BIM readiness is proposed by Liao et al (2020); however, this framework is only applicable on project level.

The survey is prepared based on this framework and consisted of 7 sections: general information, a section on strategy, organizational structure, people and culture, BIM processes, ICT infrastructure and data structure (Figure 3.2). The model defined six BIM maturity levels: Level 0 – Not present, Level 1 – Initial, Level 2 – Managed, Level 3 – Defined,

Level 4 – Quantitatively managed and Level 5 – Optimized (Siebelink, 2017). The summary of each level characteristics is presented in Table 3.1

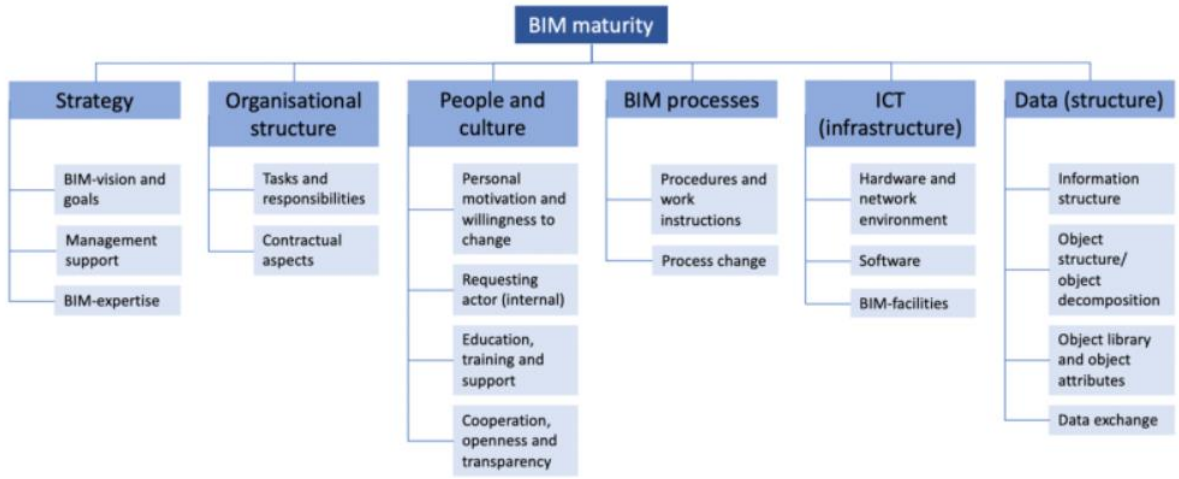


Figure 3.2: Framework for measuring BIM maturity level of organization (Siebelink, 2017)

Table 3.1: Overview of BIM Maturity Level (Siebelink, 2017)

Characteristics	**Level 0 – Not present**	**Level 1 – Initial**	**Level 2 – Managed**	**Level 3 – Defined**	**Level 4 – Quantitatively managed**	**Level 5 - Optimized**
Well-defined BIM processes, goals and strategies	None	Limited presence of well-established best practices.	Project-based, with goals outlined for the most fundamental of external processes.	Strategy-based BIM goals, a transparent overview of performance and progress, and the application of best practices.	Quality programs to verify BIM project progress and outcomes, measurable objectives	Continuous process enhancement.
Organizational structure	Not supporting BIM	Not supporting BIM	Insufficient alignment with BIM goals.	Concentrated on cooperation	Utilize BIM to improve competitive position.	Transparency and openness to foster intensive BIM-based collaboration
BIM collaboration	None	Cooperation is not coordinated with other parties	Acknowledged importance of BIM collaboration	Achieve and coordinate common goals.	Part of the strategy.	Intensive collaboration, mutual financial dependence, and mutual trust.
Success of BIM projects		Unpredictable and dependent	Following, modifying, and	Motivation and trust in	BIM processes are	Insight into and exchange of

	on the skills and abilities of the project team.	evaluating BIM processes is limited.	common BIM goals.	objectively mastered to the project partners' satisfaction.	performanc e metrics in order to anticipate issues.

3.3. Important Actors in BIM Process

The BIM process involved many different actors and the actors involved differ between organizations and projects. Because of this difference, an interview is conducted with the Corporate BIM Manager to find out which actors and/or actor group are key for the success of BIM implementation. Both categories of technical user and non-technical user identified in section 2.4 would be included. The set of scenarios which required the cooperation of the key actors were also identified. The copy of interview questions and interview summary can be found in Appendix B

3.4. Barriers in BIM Implementation

Following the interview with the Corporate BIM Manager, a series of focus group interviews was conducted involving staff from the BIM, Planning, Quantity Surveying, and Finance departments. The focus group interviews consisted of four sessions, with all selected staff members from each department participating together. A total of four focus group interview sessions were conducted, with ten participants representing various departments: four from BIM, two from Planning, two from Quantity Surveying, and two from Finance. The selection of participants aimed to include both managerial and specialist staff members from each department to ensure a comprehensive understanding of departmental operations.

The focus group interview was chosen for several reasons. Firstly, it required less time to arrange, and conduct compared to one-on-one interviews, allowing for a comprehensive understanding of barriers in the organization. This method facilitated the collection of rich qualitative data at a reasonable speed, as focus group sessions only required a moderate time commitment from participants and the interviewer. Secondly, focus groups were beneficial in exploring participants' understanding and experiences regarding the issue and the reasons behind their thinking patterns. This was crucial for the thesis objective of identifying barriers to BIM implementation. Lastly, the focus group format enabled interaction among participants, fostering immediate feedback and clarification, ultimately facilitating quicker consensus on department-level barrier experiences rather than focusing solely on personal perspectives. At the beginning of the session, all participants were brief about this aspect of the interview.

Each interview session lasted for 30 minutes, and detailed notes were taken on paper to record the discussion. No audio recordings were made during the interviews, and sensitive topics were not discussed. The copy of interview questions and interview summary can be found in Appendix C.

The purpose of the interview was to identify the challenges faced by staff members of each department during the adoption of BIM and gather their suggested solutions to overcome these difficulties. The interview was structured into two sections. In Section 1, participants were asked about their roles, responsibilities, and level of involvement in the organization, as

well as their understanding of BIM. If their response differed significantly from the definition of BIM used in the thesis, the common understanding was provided to align their understanding. Section 2 focused on participants recalling their most recent BIM project and sharing the difficulties they encountered during that project. The barriers discussed were selected based on their similarities and generalizability among the participated department.

3.5. Proposed Interventions and game model verification

Following the discussion of difficulties faced in their previous BIM projects, the interviewees were asked to propose potential solutions or improvements for these challenges. They were then asked to evaluate the current measures implemented in BIM adoption and identify areas where they believed further improvement was needed. The interventions suggested were selected based on similarities and generalizability among the participants. Practicality from the organization's perspective was also taken into consideration, as the study aimed to provide solutions to improve the BIM adoption process within the organization. The responses were tabulated, summarized, and categorized into specific interventions, which would serve as input for the game model. The selection of possible interventions was based on their alignment with participants' input and the feasibility of implementation within the organization.

Finally, the participants were asked to verify the game model by providing input on various aspects. These included:

- Verification of description and procedure for each of the identified typical collaboration procedures: The participants were asked to review and confirm the accuracy of the description and procedure for each collaboration scenario. They could provide feedback if any part was unclear or needed further clarification.
- Input for the number of staff: Participants were requested to provide an estimate of the number of staff involved in each collaboration procedure. This input helps in understanding the staffing requirements for different types of collaborations.
- Input for software used in each task: The participants were also asked to provide information on the software used for each task within the collaboration procedures. This helps in identifying the specific tools and technologies utilized for different aspects of collaboration.

The purpose of this verification process was to minimize inconsistencies in estimation caused by external factors such as project size, project nature, team composition, and team dynamics. By allowing participants to discuss and reach a consensus within their department, the aim was to obtain a more unified and reliable result. Since the objective of the thesis is to provide practical and generalizable solutions from an organizational perspective, agreement between participants within a department is essential. This ensures that the findings and recommendations are applicable and relevant to the specific department and can be potentially generalized to other similar organizational contexts.

3.6. Effectiveness of Interventions

The main framework to be used in this study to evaluate the effectiveness of interventions would be cooperative game theory. Firstly, the overview of game theory would be described.

Secondly, cooperative game theory and its benefit sharing scheme is presented. Finally, based on these frameworks, the details approach to model the research problem is outlined.

3.6.1. Overview of Game Theory

In real-world scenarios, decision making often involves interactions among multiple stakeholders. People face alignment or conflict with others when making decisions. Cooperative or noncooperative processes can lead to decisions made by groups, teams, or organizations. This has driven experts to focus on Game Theory, which studies the interactions of decision makers (Marden & Shamma, 2015). A game is defined by decision makers, their available options, their objectives, and their knowledge of the interaction structure. Game theory provides a logical method to predict outcomes in games and involves mathematical models of conflict and cooperation among rational decision makers. It can be used as a modeling tool in societal and distributed engineered systems and applied to various social decision problems (Marden & Shamma, 2015). Game theory has applications in predicting outcomes, enhancing decisions, and providing explanations (Webster, 2009). In a game theory model, decision makers are assumed to be rational and make strategic choices based on their knowledge and expectations of others' behavior. The game model consists of three key components: players, payoffs, and strategies. Players are the decision makers in the game, and each player selects a strategy, which represents their plan of possible actions. The payoffs assigned to each player's outcome depend not only on their own strategy but also on the strategies chosen by other players. Payoffs are numerical representations of the outcomes based on the collective set of strategic actions taken by all players in the game.

There are two classes of game: cooperative games, where players form coalitions to achieve their goals, and noncooperative games, where players act individually to maximize their own profit (Elkind & Rothe, 2016).

Game theory has proven to be a valuable approach in addressing various challenges in management processes and construction engineering (Kapliński & Tamošaitiene, 2010). In the realm of project management, motivating stakeholders and employees to embrace Building Information Modeling (BIM) for improved efficiency and effectiveness is crucial. Additionally, project managers often engage in negotiations to accomplish their objectives. In this context, game theory provides a framework for analyzing the knowledge and strategies employed during these processes. By utilizing game theory, it becomes possible to comprehend the interactions and contributions of different actors involved in teamwork projects (Bočková et al., 2015).

3.6.2. Cooperative Game Elements

The application of game theory in understanding the implementation of Building Information Modeling (BIM) has shown promising results. Researchers such as Turk (2016) have highlighted game theory as a suitable theoretical tool for studying the factors that hinder or promote BIM adoption. Game theory provides a framework for analyzing BIM implementations and has been used in the context of Integrated Project Delivery (Teng, 2017), which is the theoretical framework for BIM collaboration. However, the utilization of game theory, particularly cooperative game theory, in studying BIM and its application is still relatively limited. Cooperative game theory, which emphasizes collective rationality,

efficiency, fairness, and equality, has been successfully employed in analyzing profit distribution (Lazar, 2000), public-private partnerships (Scharle, 2002), and project management in related fields (Shen, 2007). Cooperative games can generate cooperative gains that surpass the sum of individual gains. However, before the concept of cooperative game theory could be applied, the following assumptions is required to satisfy (Branzei et al., 2008):

- All the players have a rational behavior and try to maximize their own share of the benefit; they are not irrational
- All players will not quit in order to achieve the profit distribution scheme
- All players can be fully trusted and there is the necessary information sharing among players
- In order to guarantee the success of the profit distribution scheme, multiple agreements to restrain the players should be established.

An n−player cooperative game in characteristic form is defined by (N, v) where $N = \{1, 2, \ldots, n\}$ denotes the set of all players. In the game (N, v), x_i is often used to represent the payoff to the ith player. The payoff vector $x = \{x_1, x_2, \cdots x_n\}$ refers to the profit getting from coalition. A characteristic function for the subset (i.e., coalition) $S \subseteq N$, denoted $v(S)$, determines the value each coalition of players can generate on its own. This characteristic function serves as input to a solution concept, which calculates the imputation or value captured by each player. The core and the Shapley value are two prominent solution concepts considered in this context.

The core represents a set of imputations where each coalition receives at least the value it can create independently, which ensure the stability of the grand coalition. It captures individual and coalitional self-interest. The nonemptiness of the core guarantee that there is at least an allocation such that no player or coalition has the incentive to leave the grand coalition. The core is defined mathematically as,

$C(N, v) = \{\boldsymbol{x} = \{x_1, x_2, \cdots x_n\} \mid \sum(i \in N)\, x_i = v(N)$

and $\sum(i \in S)\, x_i \geq v(S)$ for all $S \subset N\}$,

where $C(N, v)$ represents the core of the game

The added-value (marginal contribution) principle, implied by the core, states that under competitive free-form interaction, a player cannot capture more value than their marginal contribution to the grand coalition. This principle ensures that excluding a player would not benefit the other players, encouraging fair value distribution.

The most important aspect in cooperative game theory is how to share the profits gained through cooperation to individual actors in the grand coalition. Shapley and Shubik proposed a Shapley value in 1954, using axiom method for profit distribution solution. The Shapley value is proven to lie close to the heart of cooperative game theory and has been applied in various conditions to allocate savings and costs (Winter, 2002). The Shapley value is a solution concept used in coalition game theory that involves fairly distributing both gains and costs to several actors working in coalition. The Shapley value is the average marginal contribution of a player across all possible coalitions. It is a unique and always-existing solution concept that

emphasizes fairness in the division of value among players. According to the Shapley value (Shapley & Shubik, 1954), the amount that the player *i* can obtain is

$$\phi_i(N, v) = \sum_{S \subseteq N \setminus \{i\}} \frac{|S|!\,(n - |S| - 1)!}{n!} (v(S \cup \{i\}) - v(S)),$$

where n is the total number of players, |S| is the number of the coalition S, *v(S)* is the profit of the coalition, *v(S ∪ {i})* is the profit of the coalition with player *i*

To clarify the calculation process of Shapley value, an example below is considered

Consider a collaborative game consisted of 3 players A, B, and C, the pay-off for each coalition is outline in Table 3.2: Example of coalition and pay-off

Table 3.2: Example of coalition and pay-off

C	Ø	{A}	{B}	{C}	{A,B}	{A,C}	{B,C}	{A,B,C}
v (C)	0	1	2	2	5	7	6	10

The Shapley value of player A would be calculated by these steps:

1. Calculate the total number of possible coalitions given the number of players, in this case where number of player n = 3 so n! = 3! = 6
2. Calculate the marginal contribution of player A in all possible coalition involved A

   v(Ø∪{A}) – v(Ø) = v(A) = 1

   v({B}∪{A}) – v(B) = v(A,B) – v(A) = 5-2 = 3

   v({C}∪{A}) – v(C) = v(A,C) – v(A) = 7-2 = 5

   v({B,C}∪{A}) – v(B,C) = v(A,B,C) – v(B,C) = 10-6 = 4

3. Calculates the number of permutations of each subset size we can have when we're constructing it out of all remaining team members excluding player A, then multiply this value with the marginal contributions of player A
   |Ø|! * (n - |Ø|- 1) = 0! * 2! = 2
   |B|! * (n - |B|- 1) = 1! * 1! = 1
   |C|! * (n - |C|- 1) = 1! * 1! = 1
   |B,C|! * (n - |B,C|- 1) = 2! * 0! = 2
4. Multiply the sum of result from previous step with the reciprocal of total number of possible coalitions The result is the Shapley value of player A, stated differently, the shared pay-off of player A from the grand coalition pay-off.
   Shapley value of player A = 1/6 * (2 * 1 + 1 * 3 + 1 * 5 + 2 * 4) = 3

The research recognizes the relevance of cooperative game theory in the context of BIM, which emphasizes collaboration among stakeholders. Utilizing BIM becomes highly advantageous when all parties participate. In this study, cooperative game theory aims to assess the effectiveness of various interventions in promoting BIM implementation within the

contractor firm. A game is considered cooperative when groups of players have agreed to collaborate and strive for shared profits, aligning with the collaborative nature of BIM within the contractor firm where employees from different departments work together towards a common BIM objective.

3.6.3. Modeling of the Research Problem

Regarding the formulation of game, there are 2 cooperative games: benefit sharing game and cost sharing game. The benefit sharing game is used to define the benefit gained from intervention. The cost sharing game is used to define the cost required to implement intervention. After the major actors are identified, possible coalition between actors would also be developed. Subsequently, the utilities for each coalition in the application of each intervention are collected through survey. These utilities would be used to calculate the Shapley value for benefit sharing and cost sharing for each intervention. Finally, the net benefit of each intervention could be finalized for comparison to select the best intervention that result in overall maximize payoff of the organization. The effectiveness of each solution (intervention) is examined within all scenario that required closed collaboration from key actors identified by the interview described in section 3.3 and would be further discussed in section 4.2

From the result gathered from interview the two game structures of benefit sharing and cost sharing could be constructed as followed.

1. Game Actors: all key actors identified through the interview in section 3.3
2. Game Pay-off:
    a. In the benefit sharing game, the payoff is determined by the increase in task value, which is calculated by multiplying the task cost in traditional scenario with the productivity improvement in terms of time saved. If the intervention reduces engineering time for task completion, the payoff increases. Conversely, if the intervention increases engineering time, the payoff decreases.
    b. Conversely, in the cost sharing game, the payoff is determined by the reduction in task cost. If the intervention increases the cost, the payoff decreases. However, if the intervention reduces the cost, the payoff increases.
    c. The overall effectiveness of the intervention, which combines the benefit sharing game and the cost sharing game, is measured as the net benefit (NB). The NB is calculated as the sum of the benefit payoff and cost payoff. Essentially, the NB represents how much additional cost the company needs to invest to achieve an additional value for the task in terms of improved productivity.
3. Game Strategy: All players participate in the game act rationally to maximize their pay-off

The objectives of using cooperative game theory are to determine which intervention would result in maximized NB for each of the collaboration scenarios.

3.6.4. Estimation of game utilities

To determine the utility of the game, the survey is sent out to the same set of participants in the survey described in section 3.1, since the participants is all employees in the department that participated in all collaborative scenario identified from section 3.2. A copy of this survey can be found in Appendix D. Each participant is asked to provide the engineering time to complete the task. To increase the reliability of the data, each major task is further divided into smaller sub-task, which was confirmed by the focus group interview with each department. The engineering time to complete major task is equal to the sum of engineering time of all sub-tasks, which would be input by the participant. The detailed of the game model is further elaborated in section 4.5, since the game model is built upon the result obtained from previous interview and survey described in the above sections.

4. Results

This chapter focuses on analyzing the data obtained through survey questionnaire and interview section described in the previous chapter. The result on the current BIM maturity level of the company is discussed in section 4.1. Section 4.2 and 4.3 identify the important actors in the BIM process and the barriers experienced by them. The proposed solutions to overcome these barriers is presented in section 4.4 and their effectiveness would be evaluated using cooperative game theory and discussed in section 4.5. Figure 4.1 presented the overview of the research result.

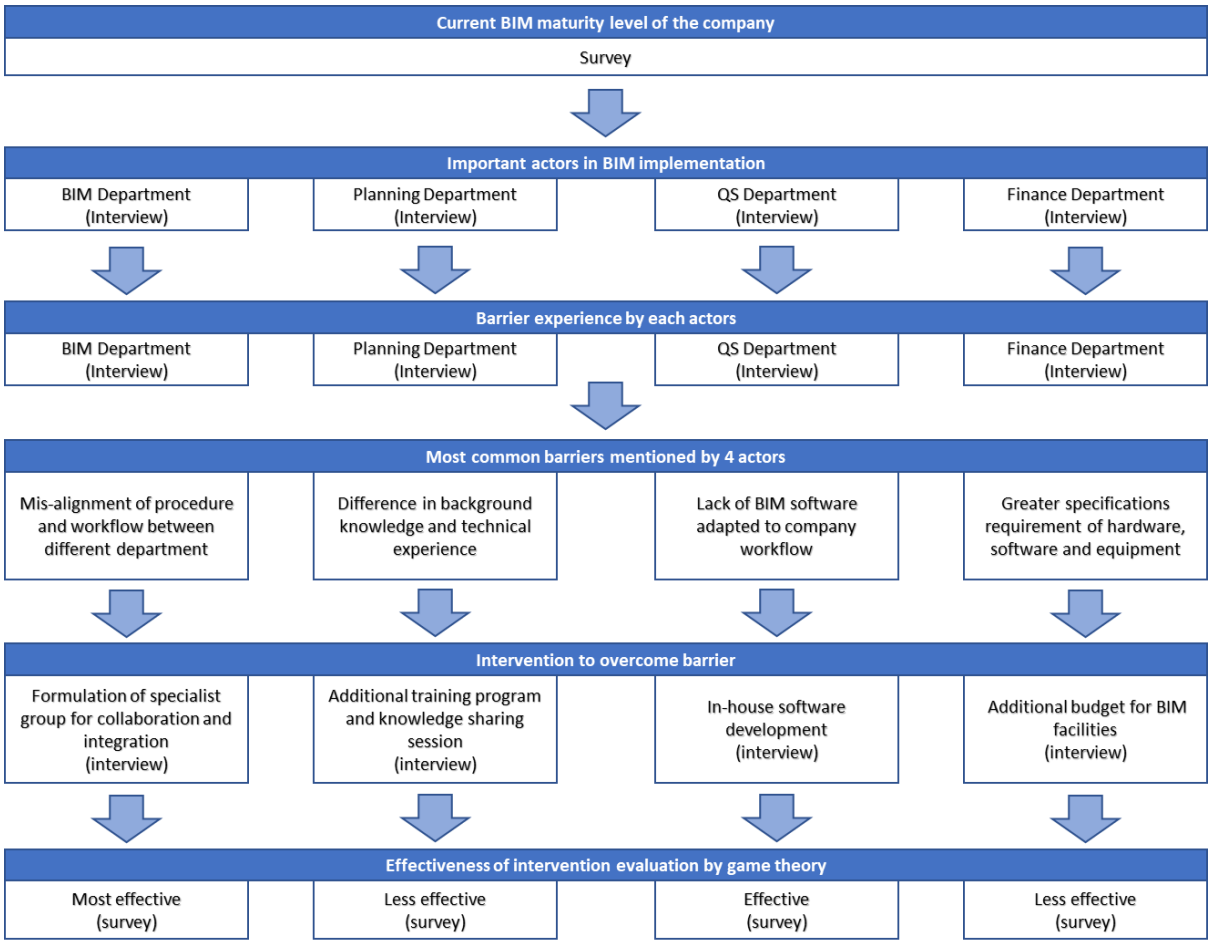


Figure 4.1: Overview of the result

4.1. Current BIM Maturity Level

Figure 4.2 provides an overview of the demographic of respondents. There are total of 35 respondents and the majority of the respondents are from BIM department, follow by QS department, Planning department and Finance department. Majority of the respondent indicated that they are often working with BIM. However, these is due to the large portion of respondent are from BIM department, where working with BIM is their major job scope. Other department indicate various familiarity with BIM. While QS department and Planning department familiarity with BIM ranging from often to sometime working with BIM, Finance department expressed that they rarely working with BIM, due to their late involvement in the overall BIM adoption process. The similar pattern could be observed in the duration of

working with BIM and the number of involved BIM project. BIM department had the most experiences working with BIM and have involved in the largest number of BIM project. Planning and QS department had relatively shorter duration of working with BIM and only have been participated in 1 to 2 BIM projects. Finance department had the shortest duration of working with BIM and is currently working on their first BIM project. The result from demographic of participants indicates that the company possesses relatively experienced BIM department and BIM implementation was took placed not only in BIM department but also in other department progressively.

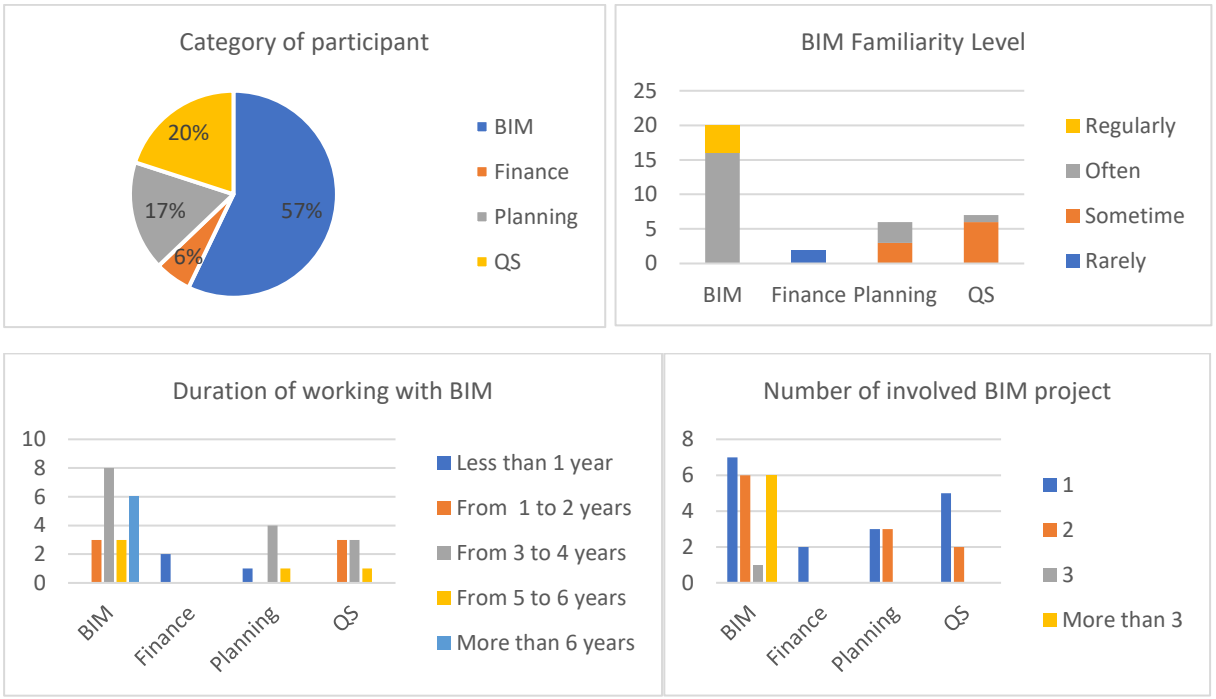


Figure 4.2: Overview of respondents

The BIM maturity scores for the categories and sub-categories is presented in Table 4.1: Average BIM maturity scores of the organization. The average score of the organization was found to be 3.21 on a scale from zero to five. The highest score of BIM maturity is in the category of ICT Infrastructure and Strategy while the lowest score of BIM maturity is in the category of Data Structure. In the sub-category, the highest score located in 'BIM vision and goal' and 'Requesting actor' while the lowest score located in 'Information structure'. The result shown that the company management level acknowledged the benefits of BIM and have invested in BIM implementation in both manpower and facilities; however, there is still potential for improvement in term of data structure and data exchange quality. All in all, the company have achieved the BIM maturity level 3 - Defined, some of the category almost reach the level 4 - Quantitatively managed' such as in Strategy and ICT while the category of Data (structure) is only achieved level 2 – Managed. However, the difference between categories is relatively limited.

In comparison between departments, BIM department have overall highest BIM maturity while Finance department have overall lowest BIM maturity, which correlated with the BIM familiarity pattern aforementioned. It is reasonable to conclude that the familiarity with BIM

affect the awareness level of BIM maturity of the organization, since the more time the employee spending in working with BIM, the more skillful they would become, hence, enhancing the organization BIM maturity. Nonetheless, the difference between BIM maturity level in 4 department is not significant.

Table 4.1: Average BIM maturity scores of the organization

(Sub-)Category	BIM	Finance	Planning	QS	Organization
Strategy	**3.98**	**3.50**	**3.50**	**3.33**	**3.74**
BIM-vision and goals	4.35	3.00	3.67	3.86	4.06
Management support	3.50	3.50	3.17	3.29	3.40
BIM-expertise	4.10	4.00	3.67	2.86	3.77
Organizational structure	**3.38**	**2.50**	**3.08**	**2.79**	**3.16**
Tasks and responsibilities	3.10	2.00	3.00	3.00	3.00
Contractual aspects	3.65	3.00	3.17	2.57	3.31
People and culture	**3.70**	**3.13**	**3.67**	**3.54**	**3.63**
Personal motivation and willingness to change	4.00	3.50	4.00	4.14	4.00
Requesting actor (internal)	4.10	3.00	4.17	4.14	4.06
Education, training, and support	3.75	4.00	3.83	3.71	3.77
Cooperation, openness, and transparency	2.95	2.00	2.67	2.14	2.69
BIM processes	**2.88**	**2.50**	**2.50**	**2.64**	**2.74**
Procedures and work instructions	3.50	3.00	3.33	3.43	3.43
Process change	2.25	2.00	1.67	1.86	2.06
ICT (infrastructure)	**3.70**	**3.67**	**3.67**	**4.10**	**3.77**
Hardware and network environment	3.40	3.50	3.17	3.86	3.46
Software	3.90	3.50	3.67	4.14	3.89
BIM-facilities	3.80	4.00	4.17	4.29	3.97
Data (structure)	**2.16**	**2.63**	**2.38**	**2.14**	**2.22**
Information structure	2.00	2.50	1.67	1.71	1.91
Object structure/ object decomposition	1.85	2.50	2.17	1.71	1.91
Object library and object attributes	2.25	3.00	3.17	2.57	2.51
Data exchange	2.55	2.50	2.50	2.57	2.54

In conclusion, the results in BIM maturity level provided an insight to the BIM capabilities of the company and indicated the noteworthy aspect in BIM implementation for improvement. These understanding would be considered in developing the potential intervention discussed in section 4.4.

4.2. Important Actors in BIM Process

The key personnel involved in the BIM process, identified after the interview are BIM department, Planning department, Quantity Surveying department and Finance department. These essential actors identified in the interview is in line with the literature presented in section 2.2 regarding involved personnel in Singapore BIM process.

As highlighted in the interview, the corporate BIM Manager acknowledges that the company has a well-organized implementation of IDD in digital design, digital fabrication and digital asset delivery, benefiting from their extensive experience with BIM and VDC adoption. The majority of projects have successfully integrated BIM for multi-disciplinary coordination, relying on construction models instead of 2D drawings during internal and external coordination meetings. This transition from 2D to 3D coordination has been ongoing for a significant period, allowing the technical department, including the BIM department, to fully embrace BIM technology in their daily work. The technical department also efficiently handles tasks such as producing as-built models and inputting FM parameters for client handover. They have developed optimized processes through multiple BIM projects, leveraging their experience in this area.

However, challenges arise when it comes to collaboration in digital construction processes involving departments outside the technical department. Solutions like digital planning progress monitoring, BIM-based cost budgeting, and 5D payment claims are only implemented in selected large-scale or government projects where IDD implementation is mandated by clients. While this client-driven motivation reduces resistance from project teams, the level of implementation and consistency of results vary. The BIM team is currently focused on scaling up successful implementations from existing projects to new ones. The government's goal with IDD is to streamline information flow across construction project parties and within construction companies. Therefore, these collaborative scenarios become increasingly relevant and necessary for maintaining the company's competitiveness in the long run.

The overall of 4 collaboration scenarios and key actors involved was summarized in Table 4.2

Table 4.2: Collaboration scenarios of department in BIM process

BIM Tasks	Coalition Structure
Project schedule monitoring and control	BIM – Planning
Cost estimating and budgeting	BIM – QS
Project cashflow monitoring and control	BIM – Planning – QS
Company cashflow monitoring and control	BIM – Planning – QS – Finance

In the context of the company, there are several key departments involved in the implementation of Building Information Modeling (BIM) and the overall project management process. The BIM department plays a central role in the organization BIM implementation, as they are responsible for strategic planning and executing the BIM implementation process. They also facilitate and support collaboration with other departments to advanced BIM applications, such as 4D and 5D solution. Additionally, the BIM department takes the lead in innovation initiatives aimed at improving overall company productivity.

The Planning department is primarily responsible for construction planning and project monitoring. They work closely with project leaders to develop construction schedules, oversee overall construction planning, and produce construction progress reports. Furthermore, they

provide support to the Quantity Surveying (QS) department in terms of progress claim and payment processes.

The QS department's main role revolves around managing the contractual framework of projects. They handle tendering and bidding processes, engage with subcontractors and suppliers, and manage project cash flow. The QS department ensures that financial aspects related to the projects are effectively monitored and controlled.

Finally, the Finance department has a comprehensive responsibility for managing the company's financial aspects. Although the focus of this thesis is on cash flow management, the Finance department oversees various financial operations within the organization. Their tasks include budgeting, financial reporting, risk management, and ensuring compliance with financial regulations.

In term of collaboration scenario, 4 typical task that required closed joint effort from 4 department are described below:

- Project schedule monitoring and control: The Planning department works closely with the BIM department to produce weekly progress reports. The Planning engineer marks up the construction plan to indicate the progress made during the previous week, while the BIM team provides the necessary information for calculating the work done compared to the overall construction scope.
- Cost estimating and budgeting: During the tendering process or when determining the budget for awarded projects, the QS department collaborates with the BIM team. The QS team utilizes detailed calculations of material and element quantities provided by the BIM department to estimate project costs accurately. This information serves as the baseline for project budgeting.
- Project cashflow monitoring and control: This task involves close collaboration between the Planning engineer and QS department. On a monthly basis, the Planning engineer advises the QS department on the location and area of completed work based on construction progress. Based on Planning team mark-up plan, BIM team generate the quantity of work completed. The QS team uses this information to calculate the total quantity completed and generates payment claims for the client. They also handle the documentation and payment response from subcontractors and suppliers, while simultaneously monitoring the project cash flow.
- Company cashflow monitoring and control: Once the QS department has completed its tasks, they transfer all relevant documentation and calculations to the Finance department. The Finance team uses this information to monitor and control the company's overall cash flow. They receive payments from clients and process payments to subcontractors and suppliers based on the project-specific details provided by the QS department.

Based on these findings, the study focuses on investigating the barriers experience by 4 departments in 4 key scenario and exploring potential solution to over these barriers

4.3. Barriers in BIM Implementation

The 10 staff members interviewed for their perspectives on BIM implementation have varying levels of familiarity with BIM, with the BIM department staff having the most experience, some of whom have worked with BIM for more than 6 years. The Planning and QS staff have approximately 2 to 5 years of experience with BIM projects, while the Finance staff are relatively new, with only 1 year of experience working with BIM.

Overall, all the interviewees have a positive view of BIM and recognize its potential benefits. They see BIM as a tool that facilitates better collaboration, communication, and a more structured approach to their work, ultimately leading to improved quality outcomes. However, they also acknowledge that there is room for improvement in company BIM implementation and that its full potential has yet to be fully utilized. They believe there are still significant barriers that need to be overcome in the implementation process. The interviewees emphasize the importance of management-level involvement in driving the pace and comprehensiveness of BIM implementation. They believe that the support and commitment of senior management are crucial for successful implementation and integration of BIM within the organization. Additionally, they express the need for continued improvements in BIM technology and processes to address the existing barriers and maximize its benefits.

4.3.1. Barriers experience by BIM department

The interview with staffs from BIM department reveal 4 barriers that need to be addressed for successful adoption, namely: *increased hardware and software requirements; resistance to changing established procedures; inadequate training and upskilling opportunities; and unsuitable software solutions.*

The first significant challenge is the greater hardware and software specifications required due to the larger sizes of BIM models and the equipment needed to view these digital models. This required additional budget allocation for BIM software and hardware, which can burden the project team, especially if the project leader is not fully committed to BIM implementation. Additionally, other departments within the organization may also need to upgrade to more expensive BIM laptops to reduce dependency on the BIM department. Furthermore, slow internet speeds can hinder model accessibility and operations, particularly when accessing the model from project site offices.

Secondly, resistance to change from traditional workflows to BIM workflows is another significant barrier. Each department typically has its well-established and optimized processes, making it challenging to persuade them to adopt BIM workflows. Overcoming this resistance requires demonstrating the benefits of BIM; however, the net benefit in BIM can be uncertain, while the investment required is clear. Moreover, the resistance to change by key personnel, such as project managers, can easily influence others who may not be directly involved in BIM development, creating additional barriers. Finding a balance in the pace of change and change capabilities is crucial. The implementation of BIM processes may take time to improve productivity, as there is a learning curve for all involved staff to understand the new workflow and gain confidence in it. Both traditional and BIM processes need to run

concurrently during this transitional period, leading to potential stress and a temporary drop in productivity. However, too gradual a change may not justify investing additional resources.

Thirdly, training and upskilling existing BIM staff and department personnel poses challenges, including transferring knowledge and lessons learned from individual use cases to the organization. BIM personnel may need more knowledge and experience in construction methods, technical aspects, and the workflows of other departments. This misalignment in communication and collaboration can impact trust levels in the output of the BIM team. Additionally, upscaling lessons learned from various use cases to the organization is challenging due to the unique nature of each project, project team composition, and project leaders. Effectively disseminating knowledge to busy individuals while highlighting the benefits remains a significant hurdle.

Furthermore, the software available in the market may not be entirely suited to the desired workflows and output formats of specific departments. Integrating such processes into existing workflows requires exploration, trials, and customization, leading to additional time and cost expenditures. Complicated software with steep learning curves can be perceived as less user-friendly, leading to reduced trust, frustration, and potential abandonment of its use.

4.3.2. Barriers experience by Planning department

There are 6 barriers were mentioned by the interviewee from Planning department, consisting of *difficulties in transitioning workflows; lack of construction method knowledge and technical expertise; increased hardware and software requirements; unsuitable software solutions; time pressure and resistance to change; and difficulties in engaging field staff*

First of all, the interviewee highlight the difficulty in transitioning from traditional workflows to BIM workflows. Many procedures within the industry have been established and refined over long periods, making it easier to control results and detect errors. Introducing BIM requires a period of adjustment and understanding for all staff involved, leading to a concurrent operation of traditional and BIM processes, which can cause stress and a temporary drop in productivity. Aligning objectives and fostering collaboration between departments can also pose challenges, as procedures need to be adjusted to increase productivity without causing significant disruption to day-to-day work.

Another barrier is the lack of construction method knowledge and technical expertise among BIM personnel. They may not be well-trained in capturing and updating construction progress or setting up monitoring systems. This knowledge gap can create communication and understanding issues between departments, hindering effective collaboration.

The greater hardware and software specifications required for BIM implementation present additional challenges. BIM models are often large and contain a vast amount of information, requiring better laptops and computers to handle them. This leads to increased project budgets, which can be burdensome for the project team, especially if the project leader is not fully committed to BIM implementation.

Furthermore, limitations in the current software available in the market pose obstacles. Many software options lack the flexibility to adapt to company procedures or output requirements

for other departments. In some cases, it may be faster and easier to stick with traditional methods rather than utilizing BIM, leading to false expectations about the capabilities of BIM. Moreover, existing software solutions do not fully address the challenges, resulting in the need to maintain multiple systems simultaneously. For instance, while BIM can monitor structural progress effectively, monitoring architectural and MEP work via BIM is still challenging. As a result, staff members must handle additional workloads with only marginal improvements in productivity.

Time pressure for change and resistance to change are also significant barriers. Initial implementation periods may experience a drop in productivity, which can discourage and frustrate employees, making them hesitant to embrace BIM fully. The instability of the implementation results at the beginning can lead to a loss of trust, prompting a return to traditional methods. Training efforts require additional time and effort, adding stress to the staff. There is also a dilemma in creating monitoring systems, as comprehensive systems require significant data input and involvement from both planning departments and field staff. However, field staff may be reluctant to participate due to perceived increased workload and a preference for hands-on work rather than computer-based tasks.

Engaging field staff in using BIM for updating construction progress presents another challenge. They may resist using BIM applications, viewing them as an additional burden on their already busy schedules. Additionally, some field staff may need more proficiency in operating digital systems and prefer their traditional work methods over sitting in front of computer screens.

4.3.3. Barriers experience by Quantity Surveying department

Similar to planning department, quantity surveying department also highlighted 5 barriers experience by them in the BIM implementation process, including *resistance to changing established procedures; time pressure; lack of technical expertise; limitations in software capabilities, and increased hardware and software requirements*

One of the significant challenges in implementing BIM within departments is the difficulty of changing well-established procedures to align with the BIM way of working. Each department has its own set of procedures that have been refined over a long period and work well for them because they have optimized them for their needs. The objective alignment and collaboration required to adjust procedures to increase productivity without disrupting day-to-day work can be a significant hurdle. Furthermore, departmental resistance comes from concerns about losing control over results and detecting errors in the new BIM process.

Time pressure also adds to the resistance for change. In the initial stages of BIM implementation, productivity is often dropped, which can discourage and frustrate staff. Trust in the new system may reduce due to its initial instability, leading some individuals to revert to traditional methods. Additionally, implementing BIM requires additional time and effort for training, further adding to the stress experienced by staff members.

The lack of technical experience and knowledge in BIM personnel is another barrier to overcome. They may not be well-versed in QS functions, quantity take-off techniques, or cost control methods. This creates difficulties in communication and understanding between

departments. BIM personnel may also need to gain familiarity with construction processes and methods, further hindering collaboration and workflow optimization.

The limitation of current software available in the market poses another challenge. Many software options need to be more well-established and customized to local work practices, requiring significant time and cost for exploration and integration into existing workflows. Moreover, these software solutions often lack the flexibility to adapt to specific company procedures or meet the output requirements of other departments. This can create false expectations about what BIM can accomplish.

The greater hardware and software specifications required for BIM due to the larger sizes of BIM models and the need for specialized equipment also present obstacles. Running large models requires better laptops and computers, increasing project budgets. The financial burden of acquiring BIM software and hardware can concern project teams, especially if the project leader is not fully committed to BIM implementation.

4.3.4. Barriers experience by Finance department

The interview with staffs from Finance department reveal 4 barriers that need to be addressed for successful adoption, namely: *software that is not well-suited to the specific needs; different background and knowledge level; incomplete implementation; and the risk of security breaches in handling sensitive data.*

The first challenge faced by Finance team in BIM implementation is the availability of software that may not be well-suited to the specific needs at hand. Slow technology development, lack of software interoperability, and non-user-friendly formats are significant reasons for this. Additionally, the software available in the market may not be well-established or customized to local work practices. As a result, a substantial amount of time and cost is often spent on exploring and trialing software integration into existing workflows. These factors can hinder the smooth adoption of BIM processes and delay the realization of its benefits.

Another obstacle to successful BIM implementation is the lack of BIM knowledge within the finance team and the technical knowledge within the BIM team. Practical and efficient systems for financial management in the BIM context are still relatively new, with limited lessons and experiences available. Furthermore, differences in educational backgrounds and technical experiences between personnel in different departments can create communication and understanding challenges.

In some cases, BIM implementation is not comprehensive, leading to partial digitalization of the job scope. While certain aspects may be digitalized, other functions may still need to be performed manually. This situation can result in the need to maintain multiple systems concurrently, increasing the risk of errors and lack of synchronization between systems.

The risk of security in handling sensitive data is another concern in BIM implementation. Finance data is highly sensitive and can have a significant impact on a company's commercial interests. Issues may arise regarding who can access and make changes to the data, potentially compromising its integrity. There is also a risk of data being leaked to outsiders, reduce a company's competitiveness and pose a threat to its intellectual property and trade secrets.

4.3.5. Summary of barriers

There are in total 15 barriers highlighted by the 10 interviewees from 4 department (Table 4.3).

Table 4.3: Overview of barriers for each department

BIM Department	Planning Department	QS Department	Finance Department
Resistance to changing established procedures	Difficulties in transitioning workflows	Resistance to changing established procedures	Incomplete implementation
Inadequate training, and upskilling opportunities	Lack of construction method knowledge and technical expertise	Lack of technical expertise	Different background and knowledge level
Unsuitable software solutions.	Unsuitable software solutions	Limitations in software capabilites	Software that is not well-suited to the specific needs
Increased hardware and software requirements	Increased hardware and software requirements	Increased hardware and software requirements	
	Time pressure and resistance to change	Time pressure	
	Difficulties in engaging field staff		Risk of security breaches in handling sensitive data.

It could be observed that although different departments mentioned different barriers, depending on their work scope and function, several common barriers were still found. After tabulating and organizing the set of barriers experienced by various departments based on their similarity, four common barriers are highlighted the most by all departments.

- Different departments have well-established functions and protocols; thus, objective alignment and collaboration is difficult. The implementation is usually not comprehensive, creating the situation where multiple systems are required to operate concurrently. This situation ultimately led to resistance to change in transitioning period due to increasing stress level and time pressure
- Digital tools are relatively new to all participating parties, and there was a steep learning curve at the start, leading to a drop in productivity at the start of implementation. Differences in background and knowledge create a gap in communication and collaboration and reduce trust level. Mindset change becomes significant obstacle
- Digital tools and technologies needed to be better established and/or customized to local work practices; therefore, substantial time and cost were spent in the exploration and trials for integrating such processes into the workflow.
- Greater specifications requirement of hardware and software or equipment needed to view digital models, due to larger sizes of BIM models

The ‘time pressure’ barriers highlighted by both QS and Planning department are partially covered by common barrier one and common barrier two presented above. There is two additional barriers, namely ‘Engaging field staff’ and ‘Risk of security breaches in handling

sensitive data' mentioned by the Planning and Finance department. These two barriers are decided to be excluded from the study because of 2 reasons. Firstly, the objective of the thesis is to examine the effectiveness of interventions from the organization's perspective; hence, the barriers identified shall be encountered by the majority of stakeholders involved. Secondly, these barriers are very specific to the function of the department; therefore, collaboration with other departments is not an effective solution for them.

Based on the identified four common barriers presented above, interventions shall be designed and discussed in the next section.

4.4. Proposed Intervention

4.4.1. Suggested solution from involved department

The participants have proposed various interventions to overcome the barriers identified. These interventions are specific to each role and are based on their highlighted barriers.

4.4.1.1. BIM department

BIM department mentioned 4 barriers, namely: *increased hardware and software requirements; resistance to changing established procedures; inadequate training and upskilling opportunities; and unsuitable software solutions.*

To address the barrier of additional budgets required for hardware and software dedicated to BIM implementation, participants suggest that this investment will yield long-term benefits in terms of increased overall productivity and company competitiveness. They propose allocating additional budgets for hardware and software, which can be controlled by utilizing network licenses for software that are not continuously used. Additionally, they recommend considering web applications, as they provide flexibility in accessing and using software without needing fixed installation points.

In order to enhance collaboration and communication between departments, participants suggest establishing a group of specialists within the BIM department. These specialists would be well-versed in both the BIM aspects and the technical aspects of the collaborated department. Their role would be to bridge the gap in operation and procedure between departments, fostering a transparent, collaborative, and open communication working environment. By working closely with staff from other departments and proactively solving their problems, trust can be built between the BIM department and other departments. This, in turn, can gradually decrease resistance and pave the way for more comprehensive collaboration.

The same group of specialists can also serve as subject experts who transfer their knowledge and experience to other staff within the BIM department. Their broader understanding of operations outside the scope of BIM enables them to train and elevate the knowledge level of their fellow BIM staff. In the long run, participants suggest implementing a knowledge management system to facilitate structured management of training programs, as well as recruitment and training for new staff.

To overcome the limitations of software available in the market, participants propose the development of in-house software solutions. While initial costs may be higher, the benefits

include license-free usage and the flexibility to adapt to company workflows and procedures. Over time, these in-house solutions can be further developed into web applications, centralizing information and allowing other departments to access the database and extract data according to their specific needs and timing.

4.4.1.2. Planning Department

There are 6 barriers mention by the planning staff during the interview, including: *difficulties in transitioning workflows; lack of construction method knowledge and technical expertise; increased hardware and software requirements; unsuitable software solutions; time pressure and resistance to change; and difficulties in engaging field staff*. In order to address the barriers mentioned, participants suggest several solutions.

Firstly, they propose the establishment of a group of facilitators from the BIM team who possess a deep understanding of the requirements, procedures, and nature of work in the planning department. These facilitators would serve as advisors to the planning staff, guiding them on effectively applying BIM solutions to their workflows. Collaboration and handholding are considered essential to ensure a smooth transition without disrupting day-to-day work. By demonstrating the time-saving benefits of using BIM, the facilitators can help build confidence and encourage the planning staff to embrace BIM.

Additionally, participants suggest implementing a training program or knowledge-sharing sessions to bridge the gap in background and experience between the planning and BIM departments. During these sessions, the planning team can share their expertise on construction methods, scheduling, and monitoring procedures with the BIM staff. At the same time, the BIM department can teach the planning staff about BIM software applications and processes. These knowledge-sharing initiatives would be mutually beneficial and foster a more comprehensive collaboration between the two departments.

Allocating additional budgets specifically for BIM hardware and software is another recommendation. Investing in better computers, software, and tools, such as smart boards and projectors, can generate greater interest and involvement from the project team in the BIM process. By providing the necessary resources, organizations can create a positive impression of BIM and technology among the project team, encouraging their active participation.

Participants acknowledge the challenges of requesting software vendors to align their products with the company's workflows. They propose an alternative solution of developing in-house software that can be adapted to the department's workflow and procedures. This flexibility allows the software to seamlessly adjust to existing processes, eliminating the need to maintain multiple systems concurrently. The familiarity between the new software and the established procedures can significantly reduce the learning curve and ease the transition for the planning staff, lowering the stress associated with learning new and complex software.

Participants emphasize the importance of close collaboration between the BIM and planning teams to reduce time pressure during the transition period. A facilitator plays a critical role in aligning the workflows and procedures of both departments, providing guidance on the best roadmap for BIM implementation. By working together and proactively solving problems,

stress levels can be reduced. The BIM team can advise the planning team on effectively incorporating BIM into their day-to-day work. In contrast, the planning staff can offer technical knowledge and assist in adjusting BIM processes to align with their planning procedures.

Engaging field staff in contributing to the BIM process can be challenging. However, participants suggest that once BIM is recognized and supported by project leaders, it becomes easier to involve field staff in updating progress for planning purposes. Mobile applications offer a viable solution in this scenario since they provide a user-friendly interface for field staff who may need to be more well-trained in complex computer software.

4.4.1.3. Quantity Surveying Department

The interview session with QS department revealed 5 barriers experience by them during BIM implementation process: *resistance to changing established procedures; time pressure; lack of technical expertise; limitations in software capabilities, and increased hardware and software requirements.* Participants suggest several interventions to address the barriers and improve the implementation of BIM in the QS department.

Similarly to the planning department, participants from the QS department also proposed the establishment of a group of facilitators from the BIM team who possess a deep understanding of the requirements, procedures, and methods used in QS and cost control. These facilitators would serve as advisors to the QS staff, guiding them on applying BIM solutions to their workflows effectively and demonstrating the time-saving benefits of using BIM in their work. Based on trust and open communication, this collaborative approach is crucial to ensuring a smooth transition without disrupting day-to-day work.

Participants emphasize the importance of close collaboration between the BIM and QS teams to reduce time pressure during the transition period. A facilitator plays a crucial role in aligning the workflows and procedures of both departments, guiding the best roadmap for BIM implementation. The BIM team can advise the QS team on how to use BIM to expedite quantity take-off and other QS tasks, while the QS staff can provide valuable technical knowledge and assist in adjusting BIM processes to align with the requirements of the QS field

Participants also suggest implementing training programs or knowledge-sharing sessions between the QS and BIM departments. During these sessions, the QS team can share their expertise on quantity take-off procedures, progress claim methods, and other QS-specific knowledge with the BIM staff. In return, the BIM department can provide training on BIM software applications and processes. These knowledge-sharing initiatives foster mutual understanding and collaboration between the departments, enabling them to work together more effectively.

In terms of software, participants recommend developing in-house software that can be designed to fit the specific workflows and procedures of the QS department. The QS staff can experience a smoother transition and a reduced learning curve by customizing the software to align with existing procedures. This approach eliminates the need to maintain multiple systems concurrently and reduces the stress of learning new and complex software.

Allocating additional budgets for BIM hardware and software is also suggested. This ensures that the QS staff have access to better computers and software tools that can enhance their ability to operate and extract data independently. By being able to evaluate data accuracy and identify errors, the QS staff can contribute to improving the overall quality of the data and streamline their workflows.

4.4.1.4. Finance department

Finance department highlighted 4 barriers, consisting of: *software that is not well-suited to the specific needs; different background and knowledge level; incomplete implementation; and the risk of security breaches in handling sensitive data.*

One of the key suggestions is the development of in-house software that can be customized to fit the specific workflows and procedures of the finance department. By tailoring the software to align with established procedures, the department can avoid the need to maintain multiple systems simultaneously. This approach reduces staff's learning curve during the transition period and minimizes the stress associated with adapting to new and unfamiliar software.

Additionally, participants propose the establishment of a group of facilitators from the BIM team who have a deep understanding of the requirements and procedures used by the finance department. The facilitators play a more crucial role in bridging the background knowledge gap between the BIM and finance departments. In comparison with BIM, Planning, and QS department, finance staff usually did not possess construction background, making the knowledge and experience gap between departments more significant.

A group of facilitators also help integrate all finance operations within the BIM platform. The finance department can benefit from improved efficiency, collaboration, and task effectiveness by having a unified platform. The integration enables stakeholders from different departments to work together seamlessly, reducing the need for rework and minimizing the risk of errors. With a single version of true financial performance reporting, all departments can be on the same page and have access to real-time information, replacing isolated systems with a comprehensive and integrated approach.

Given the sensitivity of financial data, it is crucial to implement proper security measures to mitigate the risk of data breaches. This includes defining clear roles and responsibilities for staff members with access to the system. As the system scales up to the organizational level, it becomes even more critical to ensure that data privacy and security protocols are in place to protect sensitive financial information.

4.4.2. Designing the proposed interventions

The suggested intervention by 4 departments for each of their experience barriers were tabulated and organized in Table 4.4

Table 4.4: Suggested intervention by involved department

Department	Barriers	Suggested Intervention	Expected effect on barriers
BIM	Resistance to changing established procedures	Formulating group of specialists for collaboration and integration	Increase trust, lower time pressure, reduce resistance

	Inadequate training, and upskilling opportunities	Creating training program and knowledge sharing session	Enhance knowledge level and reduce background difference
	Unsuitable software solutions.	Development of in-house software	Adapt to company procedure and requirement
	Increased hardware and software requirements	Additional budget for BIM facilities	Enhance productivity and get buy-in from upper level
Planning	Difficulties in transitioning workflows	Formulating group of specialists for collaboration and integration	Increase trust, lower time pressure, reduce resistance
	Lack of construction method knowledge and technical expertise	Creating training program and knowledge sharing session	Enhance knowledge level and reduce background difference
	Unsuitable software solutions	Development of in-house software	Adapt to company procedure and requirement
	Increased hardware and software requirements	Additional budget for BIM facilities	Enhance productivity and get buy-in from upper level
	Time pressure and resistance to change	Formulating group of specialists for collaboration and integration	Increase trust, lower time pressure, reduce resistance
	Difficulties in engaging field staff	Getting support for project leaders	Get more involvement from field staff
Quantity Surveying	Resistance to changing established procedures	Formulating group of specialists for collaboration and integration	Increase trust, lower time pressure, reduce resistance
	Lack of technical expertise	Creating training program and knowledge sharing session	Enhance knowledge level and reduce background difference
	Limitations in software capabilites	Development of in-house software	Adapt to company procedure and requirement
	Increased hardware and software requirements	Additional budget for BIM facilities	Enhance productivity and get buy-in from upper level
	Time pressure	Formulating group of specialists for collaboration and integration	Increase trust, lower time pressure, reduce resistance
Finance	Incomplete implementation	Formulating group of specialists for collaboration and integration	Advice in synchronizing various function to 1 platform
	Different background and knowledge level	Formulating group of specialists for collaboration and integration	Enhance knowledge level and reduce background difference
	Software that is not well-suited to the specific needs	Development of in-house software	Adapt to company procedure and requirement
	Risk of security breaches in handling sensitive data.	Implementing robust security framwork	Reduce risk of security breach

Four interventions have been identified as the most commonly suggested by the four involved departments. The intervention that received the highest number of suggestions involves formulation of a specialist group focused on collaboration and integration. This group would serve as a facilitator, bridging the gap between different procedures and background knowledge. They would also act as advisors and trainers, improving the technical understanding of BIM staff and providing guidance on integration initiatives for other

departments. Their efforts would reduce time pressure during the transition period and consequently reduce resistance to change from other departments. The next intervention is establishing a training program and knowledge-sharing sessions among departments. This initiative aims to foster a common understanding and enhance the departments' overall knowledge level. All four departments also proposed the development of in-house software and allocating additional budget for BIM facilities. These two interventions specifically target reducing the learning curve for non-BIM staff regarding new software, achieving better integration with the company's existing workflow, enhancing the ability to operate and extract data independently, and gaining buy-in from project teams regarding the benefits of BIM implementation.

These four interventions are closely linked to the four common barriers identified in the previous section 4.3. Each intervention is designed to address and overcome specific barriers. The relationship between the barriers and interventions is outlined as Table 4.5 follows:

Table 4.5: Interventions to overcome BIM barriers

Barrier for efficient collaboration	Interventions to overcome barriers
Different department have their own well-established function and protocols; thus, objective alignment and collaboration is difficult. The implementation is usually not comprehensive, creating the situation where multiple systems are required to operate concurrently. This situation ultimately led to resistance to change in transitioning period due to increasing stress level and time pressure	Intervention 1: Formulation of specialist group for collaboration and integration
Digital tools are relatively new to all participating parties and there was a steep learning curve at the start, leading to a drop in productivity at the start of implementation. Difference in background and knowledge create the gap in communication and collaboration and reduce trust level. Mindset change become significant obstacle	Intervention 2: Additional training program and knowledge sharing session
Digital tools and technologies were not well established and/or not customized to local work practices; therefore, substantial amount of time and cost were spent in the exploration and trials for the integration of such processes into the workflow.	Intervention 3: In-house software development
Greater specifications requirement of hardware and software or equipment needed to view digital models, due to larger sizes of BIM models	Intervention 4: Additional budget for BIM facilities

The effectiveness of each intervention would be tested in 4 typical collaboration scenarios identified in section 4.2, using cooperative game theory.

4.5. Effectiveness of Intervention

The following section begins by outlining the application of cooperative game theory in modeling the problem at hand. It then proceeds to provide an analysis of the effectiveness of

interventions in each scenario, as well as the overall effectiveness of each intervention across all scenarios. The subsequent subsection focuses on a practical case study aimed at validating the effectiveness of the interventions in a real-world context. Lastly, the section concludes by summarizing the key findings derived from the research.

4.5.1. Game Model

The study examined the effectiveness of four interventions in four collaboration scenarios using cooperative game theory. The assessment of a specific intervention's effectiveness in a given scenario involved measuring the net benefit (NB). This was calculated by subtracting the intervention's benefits from the cost of implementation. The process to calculate the net benefit for a particular intervention in a specific scenario included: (1) identifying the players involved in the overall game model, (2) quantifying the intervention's benefits using engineering time data collected through surveys, (3) determining the intervention's cost using engineering time data collected through surveys, and (4) subtracting the cost from the benefits to derive the net benefit of the intervention.

The formulation of the cooperative game involves two distinct games: the benefit sharing game and the cost sharing game. In both games, there are three actors involved: Actor A representing the traditional department responsible for specific tasks, Actor B representing additional BIM Modelers, and Actor C representing additional BIM Specialist (BSP) personnel.

Within the context of the studied contractor firm, the BIM personnel specialize in the creation and maintenance of BIM models, albeit possessing limited knowledge of information management. Conversely, the BIM Specialist, occupying a more senior position, focuses on the management of building information and digital technology. However, due to training and budget constraints, the BIM Specialist team is smaller compared to the BIM Modeler team. The grand coalition represents the collaborative effort between the traditional department team, the BIM Modeler, and the BIM Specialist, adhering to established workflow and modeling standards. The classification of actors in this manner is driven by the supportive nature of the BIM department. In the company's context, the BIM and BSP personnel play a supportive role, aiding other departments in executing their core functions more efficiently. Consequently, their primary function involves fostering cooperation with the traditional team.

Due to the supportive nature of the BIM department, the actors are defined in this manner, with BIM and BSP personnel playing a supporting role for other departments to execute their main functions more efficiently. As a result, there are a total of seven possible coalitions: A, B, C, A+B, A+C, B+C, and A+B+C. However, since players B and C do not produce any utility without the involvement of player A, this leads to four collaboration team setups.

1. Collaboration Team 1 consists of the traditional department working independently to complete a specific task before BIM implementation.
2. Collaboration Team 2 involves the traditional team supported by BIM personnel.
3. Collaboration Team 3 comprises the traditional team supported by BSP personnel.
4. Collaboration Team 4 represents the grand coalition of the game, where the traditional team is supported by both BIM and BSP personnel.

5. The details composition of each team in each collaboration scenario is determined from the interview with each departments mentioned in section 4.2

Table 4.6: Collaboration team composition in various scenario

	Collaboration Team 1	Collaboration Team 2	Collaboration Team 3	Collaboration Team 4
Project schedule monitoring and control	2 planning staffs	2 planning staffs 2 BIM staff	2 planning staffs 2 BSP staff	2 planning staffs 2 BIM staffs 1 BSP staff
Cost estimating and budgeting	3 QS staffs	3 QS staffs 3 BIM staffs	3 QS staffs 3 BSP staffs	3 QS staffs 3 BIM staffs 1 BSP staff
Project cashflow monitoring and control	2 planning staffs 3 QS staffs	2 planning staffs 3 QS staffs 3 BIM staffs	2 planning staffs 3 QS staffs 3 BSP staffs	2 planning staffs 3 QS staffs 3 BIM staffs 1 BSP staff
Company cashflow monitoring and control	2 planning staffs 3 QS staffs 2 finance staffs	2 planning staffs 3 QS staffs 2 finance staffs 3 BIM staffs	2 planning staffs 3 QS staffs 2 finance staffs 3 BSP staffs	2 planning staffs 3 QS staffs 2 finance staffs 3 BIM staffs 1 BSP staff

This formulation allows for the analysis and evaluation of the effectiveness of interventions in different collaboration scenarios, assessing the benefits and costs associated with each team setup within difference collaboration scenario. By considering these various collaborations, the study can provide insights into the effectiveness of interventions and the overall impact on the effectiveness of interventions in BIM implementation.

Furthermore, the deterministic tasks list was confirmed by the focus group interview with each department (Table 4.7). The engineering time to complete every sub-task was collected using survey described in section 3.6.4. The engineering time to complete major task is equal to the sum of engineering time of all sub-tasks.

Table 4.7: Major Tasks and Sub-Tasks

	Project schedule monitoring and control	Cost estimating and budgeting	Project cashflow monitoring and control	Company cashflow monitoring and control
Collaboration team 1: Traditional	1. Setting up monitoring system 2. Gathering construction information 3. Update construction schedule 4. Generate mark up plan	1. Studying construction drawing 2. Quantity takeoff 3. Tabulation	1. Setting up monitoring system 2. Gathering construction information 3. Update construction schedule 4. Generate mark up plan 5. Quantity take-off 6. Tabulation for payment claim	1. Setting up monitoring system 2. Gathering construction information 3. Update construction schedule 4. Quantity take-off 5. Tabulation for payment claim

			7. Gathering document from subcon 8. Tabulation for payment response	6. Gathering document from subcon 7. Tabulation for payment response 8. Input to financial system 9. Verification and monitoring 10. Cashflow summary
Collaboration team 2: Traditional + BIM	1. Setting up monitoring system 2. Setting up model 3. Gathering construction information 4. Update construction schedule 5. Generate mark up plan	1. Constructing model 2. Quantity takeoff 3. Tabulation	1. Setting up monitoring system 2. Setting up model 3. Gathering construction information 4. Update construction schedule 5. Generate mark up plan 6. Quantity take-off 7. Tabulation for payment claim 8. Gathering document from subcon 9. Tabulation for payment response	1. Setting up monitoring system 2. Setting up model 3. Gathering construction information 4. Update construction model 5. Quantity take-off 6. Tabulation for payment claim 7. Gathering document from subcon 8. Tabulation for payment response 9. Input to financial system 10. Verification and monitoring 11. Cashflow summary
Collaboration team 3: Traditional + BSP	1. Setting up monitoring system 2. Setting up model 3. Gathering construction information 4. Update construction schedule 5. Generate mark up plan	1. Constructing model 2. Quantity takeoff 3. Tabulation	1. Setting up monitoring system 2. Setting up model 3. Gathering construction information 4. Update construction schedule 5. Generate mark up plan 6. Quantity take-off 7. Tabulation for payment claim 8. Gathering document from subcon	1. Setting up monitoring system 2. Setting up model 3. Gathering construction information 4. Update construction model 5. Quantity take-off 6. Tabulation for payment claim 7. Gathering document from subcon

			9. Tabulation for payment response	8. Tabulation for payment response 9. Input to financial system 10. Verification and monitoring 11. Cashflow summary
Collaboration team 4: Traditional + BIM + BSP	1. Setting up monitoring system 2. Setting up model 3. Gathering construction information 4. Update construction schedule 5. Generate mark up plan	1. Constructing model 2. Quantity takeoff 3. Tabulation	1. Setting up monitoring system 2. Setting up model 3. Gathering construction information 4. Update construction schedule 5. Generate mark up plan 6. Quantity take-off 7. Tabulation for payment claim 8. Gathering document from subcon 9. Tabulation for payment response	1. Setting up monitoring system 2. Setting up model 3. Gathering construction information 4. Update construction model 5. Quantity take-off 6. Tabulation for payment claim 7. Gathering document from subcon 8. Tabulation for payment response 9. Input to financial system 10. Verification and monitoring 11. Cashflow summary

To get the Shapley value of the players in the grand coalition, the payoffs of all possible coalition in the grand coalition need to be determined. The pay-off for each possible coalition in both cost-sharing and benefit-sharing game is calculated from the data of engineering time collected by the survey. Finally, the Shapley value of each intervention in each scenario could be determined. The typical scenario calculation is presented in Table 4.8 below.

Table 4.8: Shapley value calculation for one typical scenario

1. Specialist group for cross-department collaboration	**Benefit Sharing Game**							
C	0	A	B	C	A + B	A + C	B + C	A + B + C
Time to complete task	0.00	57.33	inf	inf	45.30	43.00	inf	42.40
Payoff	0.00	3505.34	0.00	0.00	4436.49	4673.79	0.00	4739.93
Shapley value (a)	4266.80							
Shapley value (b)	177.24							
Shapley value (c)	295.89							
Sum of Shapley Value	4739.93							
	Cost Sharing Game							
C	0	A	B	C	A + B	A + C	B + C	A + B + C
Payoff	0.00	-3505.34	0	0	-3089.09	-3273.42	0	-3614.15
Shapley value (a)	-3754.32							
Shapley value (b)	-100.02							
Shapley value (c)	-181.59							
Sum of Shapley Value	-4035.94							

The engineering time for each sub-task in the model is equal to average of engineering time input by each participant. The total engineering time for 4 major tasks in 4 scenarios equal to the sum of engineering time of all sub-tasks. It could be observed from table 4 that the engineering time to completed task in the case to coalition B, C and B+C is set to be infinitive; since the BIM Modeler and BIM Specialist are not capable to complete the task without the traditional department involvement.

From the engineering time, the cost for each sub-task is calculated by multiplying the average engineering time (in hours) to the hourly rate of manpower cost and software cost. The total cost of 4 major tasks in 4 scenarios equal to the sum of cost of all belonging sub-tasks. The hourly rate of manpower cost is calculated through the monthly salary of staff, similarly, the hourly rate of software is calculated through the annual cost of software. The workweek of 40 hours is assumed. The set of software used in this study would be BIM modelling software, Office application, PDF reader, 4D&5D software and financial software. Using this method, the utility for each coalition in the cost sharing game is determined. To clarify, the detailed formular for calculation the cost of coalition for player A when applied intervention 1 in the first scenario of Project schedule monitoring and control is presented below:

Let $\text{Cost}_{\text{Intervention 1 | Scenario 1}}(A)$ is the cost of coalition for player A when applied intervention 1 in the first scenario of Project schedule monitoring and control then

$\text{Cost}_{\text{Intervention 1 | Scenario 1}}(A) = \text{Cost}_{\text{Intervention 1 | Sub-task 1}}(A) + \text{Cost}_{\text{Intervention 1 | Sub-task 2}}(A) + \text{Cost}_{\text{Intervention 1 | Sub-task 3}}(A) + \text{Cost}_{\text{Intervention 1 | Sub-task 4}}(A)$

where $\text{Cost}_{\text{Intervention 1 | Sub-task 1}}(A) = \text{Time}_{\text{Intervention 1 | Sub-task 1}}(A) * \text{Manpower rate}_{\text{Intervention 1 | Sub-task 1}}(A) + \text{Time}_{\text{Intervention 1 | Sub-task 1}}(A) * \text{Software rate}_{\text{Intervention 1 | Sub-task 1}}(A)$

using this method, cost of coalition A when applied intervention 1 in scenario 1 is 3505.34, calculation is similar for other cost components for all coalition

From the engineering time, the utility of each coalition in the benefit sharing game is the work value, calculated by multiplying the cost of traditional team (baseline work value) to the ratio of engineering time of traditional team and engineering time of coalition. To clarify, the detailed formular for calculation the cost of coalition for player A when applied intervention 1 in the first scenario of Project schedule monitoring and control is presented below:

Let $\text{Benefit}_{\text{Intervention 1 | Scenario 1}}(A+B)$ is the cost of coalition for player A and player B when applied intervention 1 in the first scenario of Project schedule monitoring and control then

$$\text{Benefit}_{\text{Intervention 1 | Scenario 1}}(A+B) = \text{Cost}_{\text{Intervention 1 | Scenario 1}}(A) * \frac{\text{Time Intervention 1 | Scenario 1 (A)}}{\text{Time Intervention 1 | Scenario 1 (A+B)}}$$

$$= 3505.34 * \frac{57.33}{45.30} = 4436.49$$

The similar method was used to calculate the utilities of both cost-sharing and benefit-sharing game for all 4 interventions in all 4 collaboration scenarios. The Shapley value of each player in both games was calculated using the formula described in section 3.6. The benefit of a specific intervention in each scenario is the sum of the Shapley values of all players in the benefit-sharing game, while the cost of a particular intervention in each scenario is the sum of the Shapley values of all players in the cost-sharing game. The net benefit (NB) of a specific intervention in each scenario is the difference between these two values. The intervention with the highest NB is considered the most effective overall.

4.5.2. Effectiveness of intervention in each collaborating scenario

This section describes the effectiveness of 4 interventions in 4 different collaboration scenarios: Project schedule monitoring and control, Cost estimating and budgeting, Project cashflow monitoring and control, Company cashflow monitoring and control

4.5.2.1. Effectiveness of intervention in Project schedule monitoring and control

The analysis of Figure 4.3 in the Project Schedule Monitoring and Control scenario reveals several key findings. Firstly, all four interventions demonstrate an increasing trend in benefits as there is greater involvement of manpower with better BIM capabilities within the coalition.

When comparing the benefits of the grand coalition, Intervention 1 generates the highest benefit, followed by Intervention 3, Intervention 2, and Intervention 4. Conversely, the costs of the grand coalitions follow the opposite pattern, with Intervention 1 having the lowest cost,

followed by Intervention 3, Intervention 2, and Intervention 4. However, the costs of each coalition vary.

In Intervention 1, the cost decreases as more BIM-capable staff join the collaboration, reaching its minimum at the grand coalition. For Intervention 2 and Intervention 3, the cost initially rises in Collaboration Team 2 but then follows a decreasing trend in Collaboration Team 3 and Collaboration Team 4. However, the cost at the grand coalition is still higher than the baseline of the traditional team. In Intervention 4, the cost increases from Collaboration Team 1 to Collaboration Team 4.

There is a clear relationship between benefits and costs. If an intervention can generate significant benefits in terms of time savings, the cost of implementing the intervention is likely to decrease. This is because reduced time spent on completing tasks leads to lower manpower and software costs.

Different scenarios emerge for each intervention regarding the grand coalition's stability. In Intervention 1, the players would be more inclined to stay in the grand coalition since it yields the highest net benefit (NB). In Intervention 2 and Intervention 3, the players would be more inclined to break the grand coalition and instead choose Collaboration Team 3, as this coalition yields the highest NB. In Intervention 4, the players would be more inclined to break the grand coalition and instead stick to the traditional team composition. By doing so, the players would not gain anything but also avoid losing benefits.

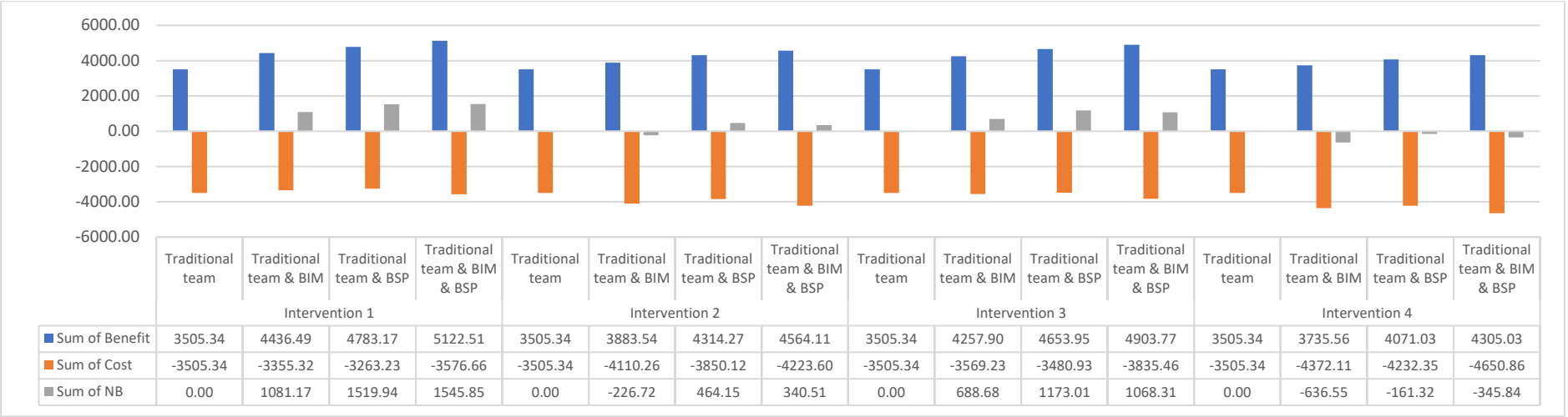
Figure 4.4 provides insights into the distribution of benefits and costs among players, as well as the net benefit (NB) of each intervention for the grand coalition and individual players in the game.

Regarding benefit distribution and cost distribution among players, the traditional team receives the highest share in both benefits and costs. In the game setting, they generate the highest utility compared to other players; hence their marginal contribution to the grand coalition is also the highest. In practical setting, they are the main actors responsible for completing the tasks, with BIM and BSP teams playing a supporting role to enhance their productivity. As a result, the traditional team's payoff in the collaborative setting is the highest.

The pattern of benefit sharing among players aligns with the pattern of benefits generated by each intervention. However, the cost sharing reveals an interesting pattern. While the cost sharing of the traditional team is negative, some of the cost sharing of the BIM and BSP teams is positive. This suggests that the involvement of BIM and BSP staff in the collaboration team reduces the overall cost rather than increasing it. If their involvement, combined with the effect of the intervention, leads to time savings and enhanced work value, their costs can be offset by the benefits they bring to the team.

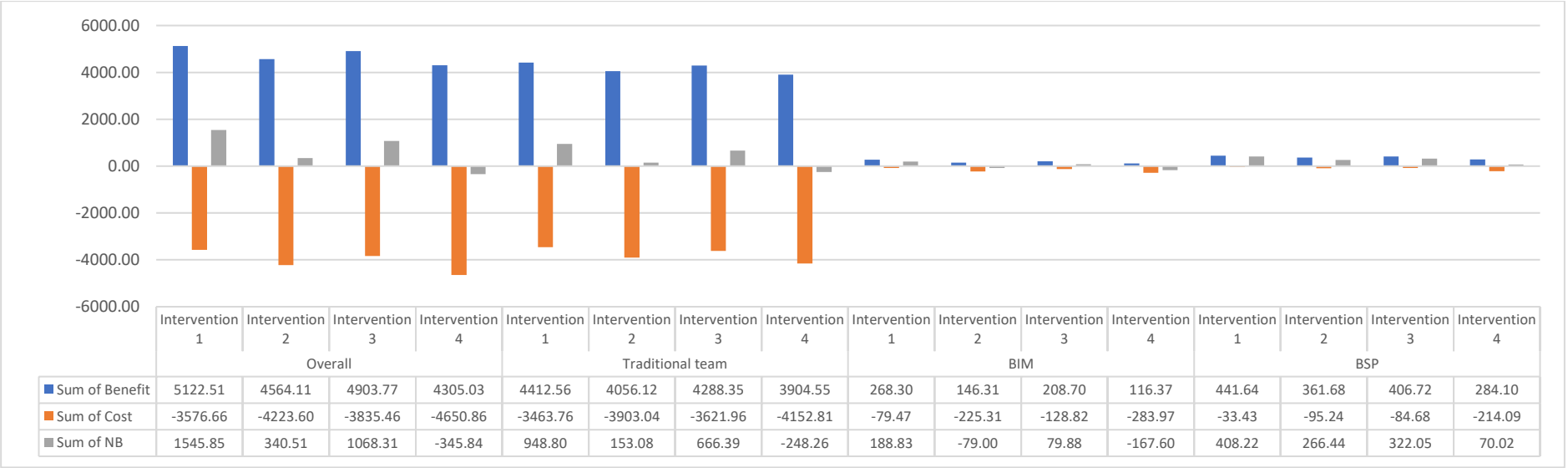
Regarding NB, Intervention 1 demonstrates the highest positive NB, followed by Intervention 3 and Intervention 2, indicating that the benefits of implementing these interventions outweigh the associated costs. However, Intervention 4 has a negative NB, indicating that the costs of implementing this intervention are higher than the benefits it produces.

When comparing between players, the traditional team receives the highest NB sharing compared to the BIM and BSP teams. Their NB pattern aligns with that of the grand coalition. Additionally, when comparing between the BIM team and BSP team, their payoff shares also follow the same pattern as the grand coalition. However, the NB of the BSP team is consistently higher than that of the BIM team. Notably, the NB of the BSP team is positive for all interventions, even for Intervention 4 with the lowest payoff. This emphasizes the importance of staff with collaboration knowledge and experience in effectively managing collaboration settings with other departments.



	Intervention 1				Intervention 2				Intervention 3				Intervention 4			
	Traditional team	Traditional team & BIM	Traditional team & BSP	Traditional team & BIM & BSP	Traditional team	Traditional team & BIM	Traditional team & BSP	Traditional team & BIM & BSP	Traditional team	Traditional team & BIM	Traditional team & BSP	Traditional team & BIM & BSP	Traditional team	Traditional team & BIM	Traditional team & BSP	Traditional team & BIM & BSP
Sum of Benefit	3505.34	4436.49	4783.17	5122.51	3505.34	3883.54	4314.27	4564.11	3505.34	4257.90	4653.95	4903.77	3505.34	3735.56	4071.03	4305.03
Sum of Cost	-3505.34	-3355.32	-3263.23	-3576.66	-3505.34	-4110.26	-3850.12	-4223.60	-3505.34	-3569.23	-3480.93	-3835.46	-3505.34	-4372.11	-4232.35	-4650.86
Sum of NB	0.00	1081.17	1519.94	1545.85	0.00	-226.72	464.15	340.51	0.00	688.68	1173.01	1068.31	0.00	-636.55	-161.32	-345.84

Figure 4.3: Intervention Benefit & Cost in different collaboration team in collaboration scenario 1



	Overall				Traditional team				BIM				BSP			
	Intervention 1	Intervention 2	Intervention 3	Intervention 4	Intervention 1	Intervention 2	Intervention 3	Intervention 4	Intervention 1	Intervention 2	Intervention 3	Intervention 4	Intervention 1	Intervention 2	Intervention 3	Intervention 4
Sum of Benefit	5122.51	4564.11	4903.77	4305.03	4412.56	4056.12	4288.35	3904.55	268.30	146.31	208.70	116.37	441.64	361.68	406.72	284.10
Sum of Cost	-3576.66	-4223.60	-3835.46	-4650.86	-3463.76	-3903.04	-3621.96	-4152.81	-79.47	-225.31	-128.82	-283.97	-33.43	-95.24	-84.68	-214.09
Sum of NB	1545.85	340.51	1068.31	-345.84	948.80	153.08	666.39	-248.26	188.83	-79.00	79.88	-167.60	408.22	266.44	322.05	70.02

Figure 4.4: Comparison of Shapley value for different actors in game in collaboration scenario 1

4.5.2.2. Effectiveness of intervention in Cost estimating and budgeting

The analysis of Figure 4.5 in the Cost Estimating and Budgeting scenario provides important insights. Comparing the benefits of the grand coalition, Intervention 1 generates the highest benefit, followed by Intervention 3, Intervention 2, and Intervention 4. Conversely, the costs of the grand coalition follow the opposite pattern, with Intervention 1 having the lowest cost, followed by Intervention 3, Intervention 2, and Intervention 4.

Similar to the previous scenario, the benefits generated by different coalitions exhibit an increasing trend as more BIM-capable personnel are involved. However, in this particular scenario, the cost of each coalition also increases with the additional involvement of more BIM-capable personnel. This can be attributed to two reasons. Firstly, unlike the previous scenario, where manual tasks were replaced by automation through BIM software, resulting in significant time savings, in this case, the time spent by the quantity surveyor (QS) on manual take-off cannot be fully offset since the BIM model needs to be constructed before automatic take-off can occur. Secondly, constructing the model and conducting quantity take-off are basic BIM tasks, and the BSP personnel's collaboration and data management expertise are not as useful. Although they possess better BIM skills and save some time in handling the model, their contribution is relatively less compared to the additional cost they bring.

The relationship between benefits and costs in this scenario mirrors that of the previous scenario. The time saved by involving more capable BIM personnel in the collaboration team is not substantial enough to offset the additional costs resulting from increased manpower and software usage.

Regarding the stability of the grand coalition, different scenarios emerge. In Intervention 1, the players would benefit more by staying in the grand coalition since it yields the highest net benefit (NB). However, in all remaining interventions, the players would benefit more by breaking the grand coalition and instead sticking to the traditional team composition. By doing so, the players would neither gain nor lose.

Figure 4.6 provides valuable insights into the distribution of benefits and costs among players, as well as the net benefit (NB) for each intervention in the game. The findings shed light on the dynamics of benefit and cost-sharing, as well as the effectiveness of the interventions.

Similar to the previous scenario, the traditional team receives the highest share in both benefits and costs among the players. This is consistent with their role as the main responsible party for completing the task, and the BIM and BSP teams play a supporting role in enhancing their productivity. The traditional team holds the largest utility in terms of work value and cost, resulting in a higher payoff in the collaborative setting.

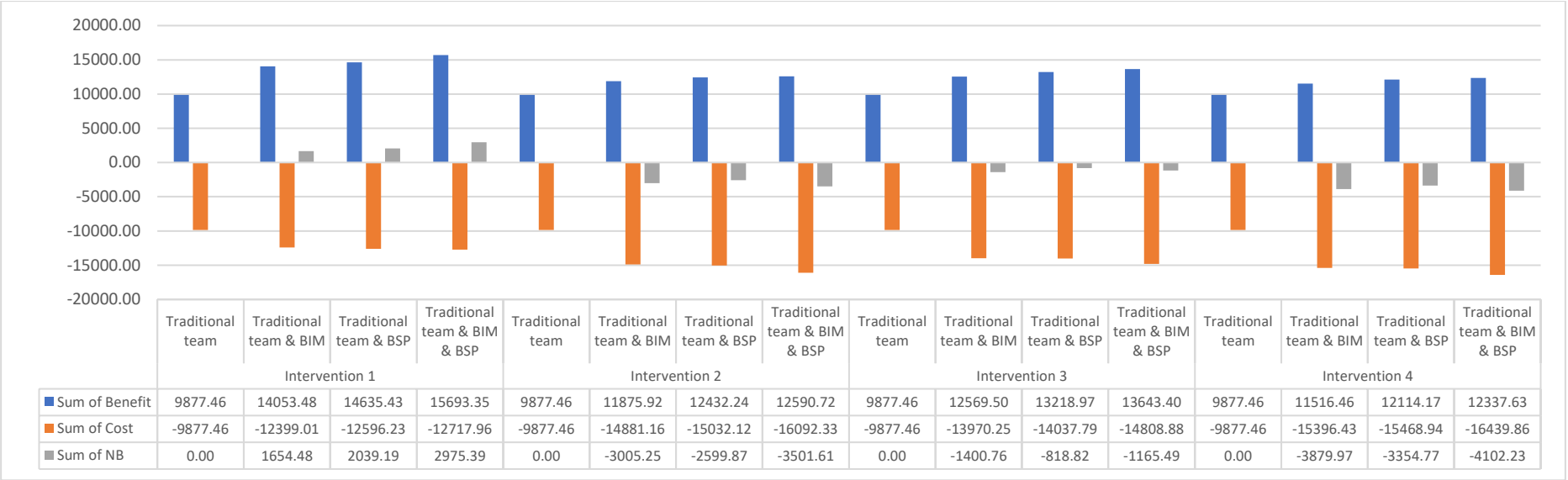
The benefit distribution among players follows a similar pattern to the benefits generated by each intervention in the grand coalition. This implies that the interventions directly impact the benefits experienced by individual players within the collaboration. It showcases the effectiveness of these interventions in enhancing the overall performance and productivity of the team.

However, a more interesting pattern emerges when considering the cost distribution among players. In contrast to the previous scenario, where the cost-sharing of the BIM and BSP teams was negative, indicating a reduction in overall costs, in this scenario, the cost-sharing for all

teams in all interventions is negative. This suggests that the involvement of more BIM-capable personnel does not lead to cost reduction but rather increases the overall cost of the task. It could be attributed to the complexity and additional resources required for the interventions implemented.

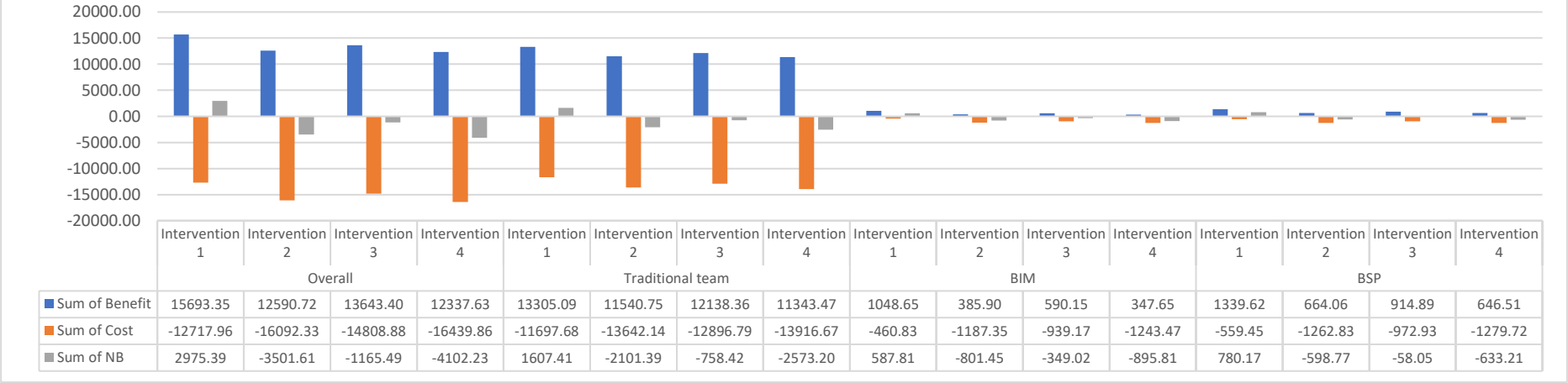
Analyzing the NB of each intervention, Intervention 1 demonstrates the highest positive NB, indicating that the benefits of implementing this intervention outweigh the associated costs. On the other hand, Intervention 2, Intervention 3, and Intervention 4 exhibit negative NB, indicating that the costs of implementing these interventions exceed the benefits they produce. Among them, Intervention 2 has the most negative NB, suggesting it to be the least effective or cost-efficient intervention in terms of the benefits achieved.

Comparing between players, the traditional team receives the highest NB sharing, aligning with their higher payoff compared to the BIM and BSP teams. Their NB pattern mirrors that of the grand coalition, highlighting their dominant position in the collaboration. Moreover, the BSP team consistently achieves a higher NB than the BIM team, emphasizing the significance of collaborating knowledge and experience in handling collaborative settings with other departments.



	Intervention 1				Intervention 2				Intervention 3				Intervention 4			
	Traditional team	Traditional team & BIM	Traditional team & BSP	Traditional team & BIM & BSP	Traditional team	Traditional team & BIM	Traditional team & BSP	Traditional team & BIM & BSP	Traditional team	Traditional team & BIM	Traditional team & BSP	Traditional team & BIM & BSP	Traditional team	Traditional team & BIM	Traditional team & BSP	Traditional team & BIM & BSP
Sum of Benefit	9877.46	14053.48	14635.43	15693.35	9877.46	11875.92	12432.24	12590.72	9877.46	12569.50	13218.97	13643.40	9877.46	11516.46	12114.17	12337.63
Sum of Cost	-9877.46	-12399.01	-12596.23	-12717.96	-9877.46	-14881.16	-15032.12	-16092.33	-9877.46	-13970.25	-14037.79	-14808.88	-9877.46	-15396.43	-15468.94	-16439.86
Sum of NB	0.00	1654.48	2039.19	2975.39	0.00	-3005.25	-2599.87	-3501.61	0.00	-1400.76	-818.82	-1165.49	0.00	-3879.97	-3354.77	-4102.23

Figure 4.5: Intervention Benefit & Cost in different collaboration team in collaboration scenario 2



	Overall				Traditional team				BIM				BSP			
	Intervention 1	Intervention 2	Intervention 3	Intervention 4	Intervention 1	Intervention 2	Intervention 3	Intervention 4	Intervention 1	Intervention 2	Intervention 3	Intervention 4	Intervention 1	Intervention 2	Intervention 3	Intervention 4
Sum of Benefit	15693.35	12590.72	13643.40	12337.63	13305.09	11540.75	12138.36	11343.47	1048.65	385.90	590.15	347.65	1339.62	664.06	914.89	646.51
Sum of Cost	-12717.96	-16092.33	-14808.88	-16439.86	-11697.68	-13642.14	-12896.79	-13916.67	-460.83	-1187.35	-939.17	-1243.47	-559.45	-1262.83	-972.93	-1279.72
Sum of NB	2975.39	-3501.61	-1165.49	-4102.23	1607.41	-2101.39	-758.42	-2573.20	587.81	-801.45	-349.02	-895.81	780.17	-598.77	-58.05	-633.21

Figure 4.6: Comparison of Shapley value for different actors in game in collaboration scenario 2

4.5.2.3. Effectiveness of intervention in Project cashflow monitoring and control

Figure 4.7 presents the cost and benefit analysis of different interventions in the Project Cashflow Monitoring and Control scenario. When comparing the benefits of the grand coalition, Intervention 1 generates the highest benefit, followed by Intervention 3, Intervention 2, and Intervention 4. Conversely, the cost of the grand coalition follows the opposite pattern, with Intervention 1 and Intervention 3 having relatively equal lowest costs, followed by Intervention 4 and Intervention 2.

Similar to previous scenarios, the benefits generated by different coalitions show an increasing trend with the additional involvement of more BIM-capable personnel. However, in this particular scenario, the cost initially rises in Collaboration Team 2 but then follows a decreasing trend in Collaboration Team 3 and Collaboration Team 4. Nevertheless, the cost at the grand coalition remains higher than the baseline of the traditional team. The differences in costs among Collaboration Teams 2, 3, and 4 exist but are relatively small.

The relationship between benefits and costs in this scenario aligns with the previous scenarios. The time saved by involving more capable BIM personnel in the collaboration team is not significant enough to fully offset the additional costs resulting from increased manpower and software usage.

Regarding the stability of the grand coalition, different scenarios emerge depending on the intervention. In Intervention 1, Intervention 3, and Intervention 4, the players would benefit more by staying in the grand coalition since it yields the highest net benefit (NB). However, in Intervention 2, the players would benefit more by breaking the grand coalition and instead choosing Collaboration Team 3, as this coalition offers the highest NB.

Figure 4.8 provides valuable insights into the distribution of benefits and costs among players, as well as the net benefit (NB) for each intervention in the game. The findings shed light on the dynamics of benefit and cost sharing, as well as the effectiveness of the interventions.

Similar to the previous scenario, the traditional team receives the highest share in both benefits and costs among the players. This suggests that the traditional team plays a central role in the project and bears the largest responsibility for completing the task. It also indicates that the interventions implemented primarily enhance the productivity and efficiency of the traditional team.

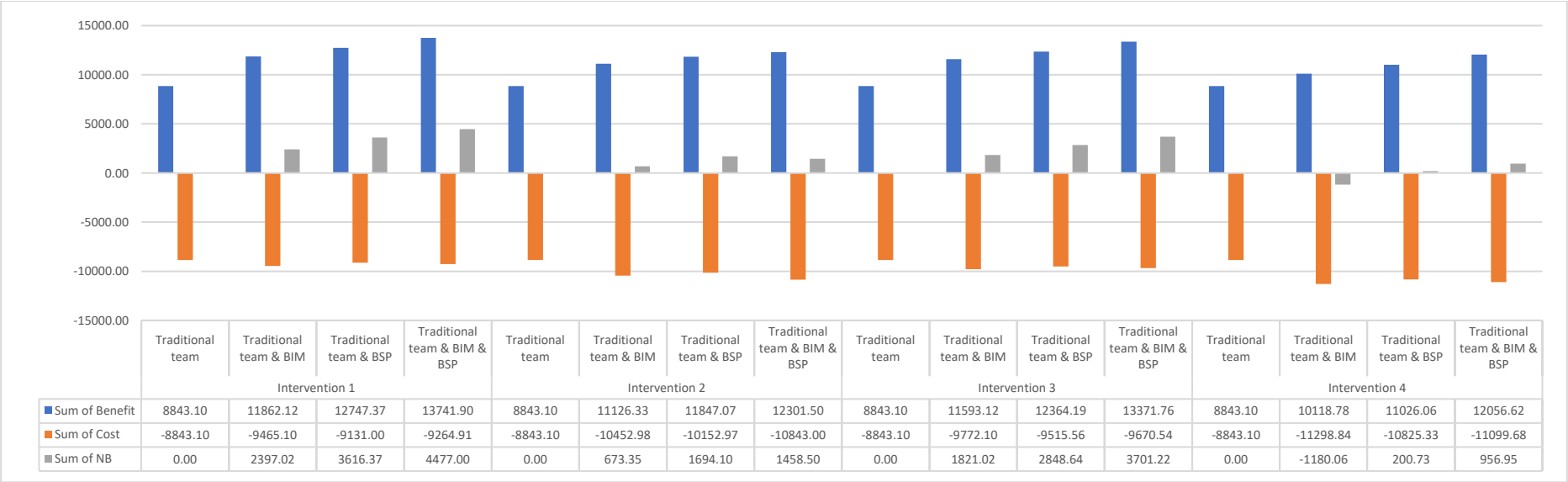
The benefit distribution among players follows a similar pattern to the benefits generated by each intervention in the grand coalition. This suggests that the interventions directly influence the benefits experienced by individual players within the collaboration. It demonstrates the effectiveness of these interventions in improving the overall performance and productivity of the team.

Similarly, the cost distribution among players aligns with the pattern of costs in the grand coalition associated with each intervention. Just like in the previous scenario, the cost sharing for all teams in all interventions is negative. This indicates that the involvement of more BIM-capable personnel does not lead to a reduction in costs but rather increases the overall cost

of the task. It suggests that the interventions implemented introduce additional complexities and resource requirements, resulting in increased costs.

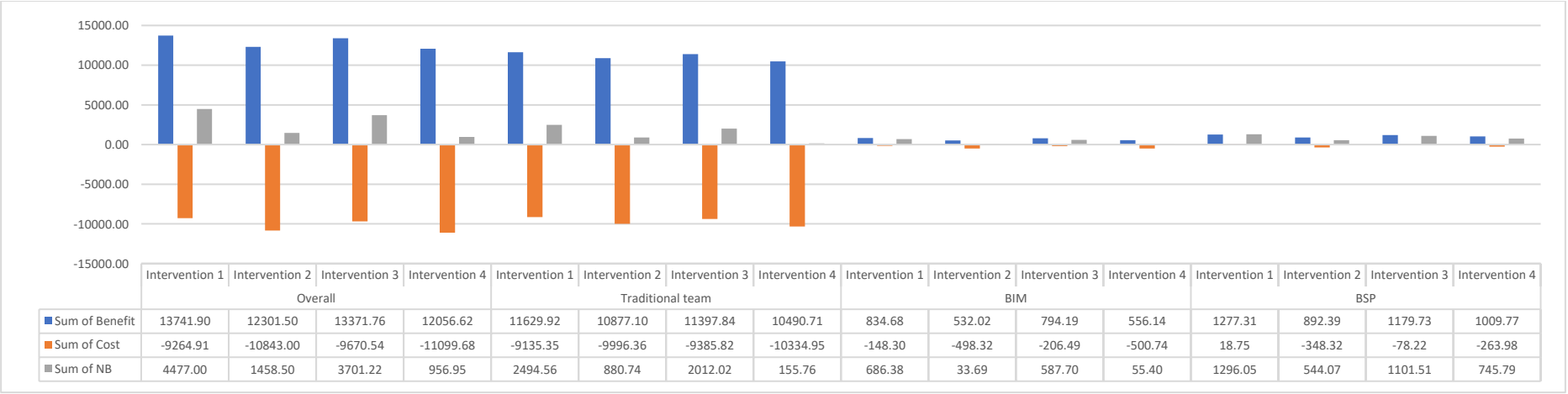
Analyzing the NB of each intervention, all interventions show positive NB, indicating that the benefits of implementing these interventions outweigh the associated costs. Intervention 1 demonstrates the highest NB, followed by Intervention 3, Intervention 2, and Intervention 4, which have relatively similar lower NB. This highlights the varying effectiveness and cost-efficiency of the interventions in generating returns on the investment made.

When comparing between players, the traditional team receives the highest NB sharing, aligning with their higher benefits and costs compared to the BIM and BSP teams. The NB pattern among players mirrors that of the grand coalition, emphasizing the dominant position of the traditional team in the collaboration. Furthermore, the BSP team consistently achieves higher NB than the BIM team, suggesting that the data management and collaboration expertise of the BSP team contribute more significantly to the overall NB.



	Traditional team	Traditional team & BIM	Traditional team & BSP	Traditional team & BIM & BSP	Traditional team	Traditional team & BIM	Traditional team & BSP	Traditional team & BIM & BSP	Traditional team	Traditional team & BIM	Traditional team & BSP	Traditional team & BIM & BSP	Traditional team	Traditional team & BIM	Traditional team & BSP	Traditional team & BIM & BSP
	Intervention 1				Intervention 2				Intervention 3				Intervention 4			
Sum of Benefit	8843.10	11862.12	12747.37	13741.90	8843.10	11126.33	11847.07	12301.50	8843.10	11593.12	12364.19	13371.76	8843.10	10118.78	11026.06	12056.62
Sum of Cost	-8843.10	-9465.10	-9131.00	-9264.91	-8843.10	-10452.98	-10152.97	-10843.00	-8843.10	-9772.10	-9515.56	-9670.54	-8843.10	-11298.84	-10825.33	-11099.68
Sum of NB	0.00	2397.02	3616.37	4477.00	0.00	673.35	1694.10	1458.50	0.00	1821.02	2848.64	3701.22	0.00	-1180.06	200.73	956.95

Figure 4.7: Intervention Benefit & Cost in different collaboration team in collaboration scenario 3



	Intervention 1	Intervention 2	Intervention 3	Intervention 4	Intervention 1	Intervention 2	Intervention 3	Intervention 4	Intervention 1	Intervention 2	Intervention 3	Intervention 4	Intervention 1	Intervention 2	Intervention 3	Intervention 4
	Overall				Traditional team				BIM				BSP			
Sum of Benefit	13741.90	12301.50	13371.76	12056.62	11629.92	10877.10	11397.84	10490.71	834.68	532.02	794.19	556.14	1277.31	892.39	1179.73	1009.77
Sum of Cost	-9264.91	-10843.00	-9670.54	-11099.68	-9135.35	-9996.36	-9385.82	-10334.95	-148.30	-498.32	-206.49	-500.74	18.75	-348.32	-78.22	-263.98
Sum of NB	4477.00	1458.50	3701.22	956.95	2494.56	880.74	2012.02	155.76	686.38	33.69	587.70	55.40	1296.05	544.07	1101.51	745.79

Figure 4.8: Comparison of Shapley value for different actors in game in collaboration scenario 3

4.5.2.4. Effectiveness of intervention in Company cashflow monitoring and control

Figure 4.9 provides insights into the cost and benefit analysis of different interventions in the Project Cashflow Monitoring and Control scenario. Comparing the benefits of the grand coalition, Intervention 1 generates the highest benefit, followed by Intervention 3, Intervention 2, and Intervention 4. Conversely, the cost of the grand coalition follows a different pattern. For Intervention 1 and Intervention 3, the costs initially rise in Collaboration Team 2 but then decrease in Collaboration Team 3 and Collaboration Team 4. The cost of the grand coalition is lower than the baseline cost. However, for Intervention 2 and Intervention 4, the costs initially rise in Collaboration Team 2 and follow a decreasing trend in Collaboration Team 3 and Collaboration Team 4. The cost of the grand coalition is higher than the baseline cost.

Similar to previous scenarios, the benefits generated by different coalitions exhibit an increasing trend with the additional involvement of more BIM-capable personnel. However, the time savings resulting from their involvement are not significant enough to fully offset the additional costs arising from increased manpower and software usage.

Regarding the stability of the grand coalition, different scenarios emerge based on the interventions. In Intervention 1 and Intervention 3, the players would benefit more by staying in the grand coalition since it yields the highest net benefit (NB). However, in Intervention 2, the players would benefit more by breaking the grand coalition and instead choosing Collaboration Team 3, as this coalition offers the highest NB. In Intervention 4, the players would benefit more by breaking the grand coalition and instead sticking to the traditional team composition, as this option neither gains nor loses them any significant benefits.

Figure 4.10 presents valuable insights into the distribution of benefits and costs among players, as well as the net benefit (NB) for each intervention in the game. These findings provide important information about the effectiveness and impact of interventions, as well as the roles played by different teams within the collaboration.

Consistent with the previous scenarios, the traditional team receives the highest share in both benefits and costs among the players. This indicates their central role in the project and their contribution to overall project outcomes. The benefit distribution among players aligns with the benefits generated in the grand coalition by each intervention, suggesting that the interventions directly influence the benefits experienced by individual players.

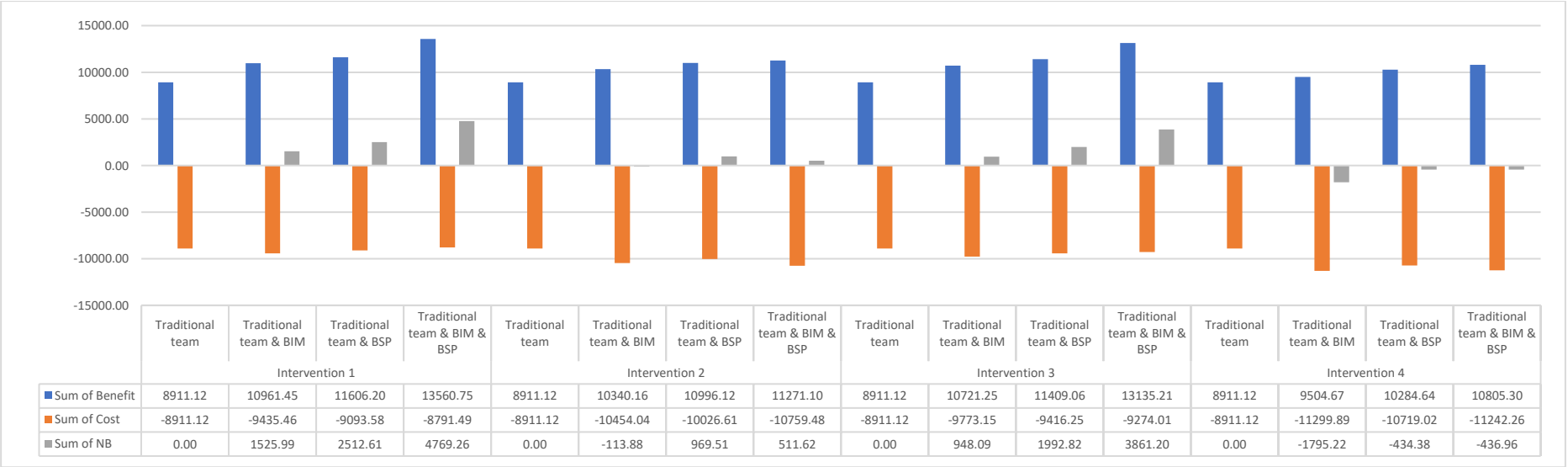
Similarly, the cost distribution among players follows the pattern of costs in the grand coalition associated with each intervention. Notably, in this scenario, both the BIM and BSP teams have positive cost sharing values, indicating that their involvement, combined with the effect of the interventions, actually reduces costs. This highlights the cost-saving potential of utilizing BIM capabilities and collaboration expertise in the project.

Analyzing the NB of each intervention, Intervention 1 demonstrates the highest positive NB, followed by Intervention 3. Intervention 2 also shows a positive NB, albeit with the lowest

value among the interventions. However, Intervention 4 has a negative NB, indicating that the costs associated with this intervention outweigh the benefits it generates.

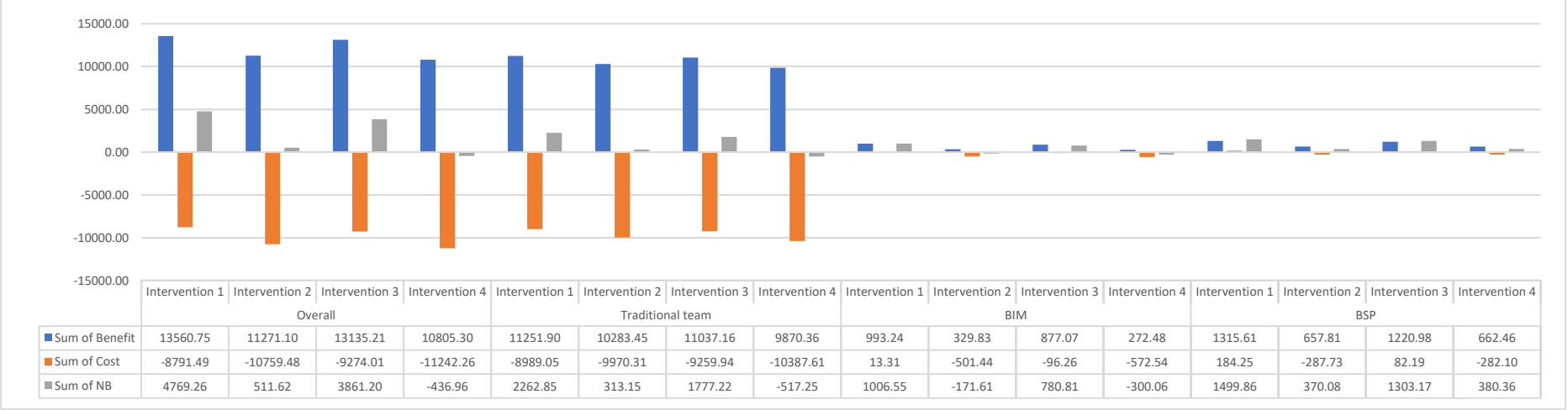
When comparing NB between players, the traditional team consistently receives the highest NB sharing, aligning with their higher benefits and costs compared to the BIM and BSP teams. The NB pattern among players reflects that of the grand coalition, highlighting the importance of the traditional team in driving overall project success.

Additionally, the BSP team consistently achieves a higher NB than the BIM team, emphasizing the significance of collaboration knowledge and experience in effectively managing collaboration settings with other departments. Notably, the NB of the BSP team is positive for all interventions, even for Intervention 4 with the lowest payoff. This underscores the crucial role of the BSP team in facilitating effective collaboration and maximizing returns on investment.



	Intervention 1				Intervention 2				Intervention 3				Intervention 4			
	Traditional team	Traditional team & BIM	Traditional team & BSP	Traditional team & BIM & BSP	Traditional team	Traditional team & BIM	Traditional team & BSP	Traditional team & BIM & BSP	Traditional team	Traditional team & BIM	Traditional team & BSP	Traditional team & BIM & BSP	Traditional team	Traditional team & BIM	Traditional team & BSP	Traditional team & BIM & BSP
Sum of Benefit	8911.12	10961.45	11606.20	13560.75	8911.12	10340.16	10996.12	11271.10	8911.12	10721.25	11409.06	13135.21	8911.12	9504.67	10284.64	10805.30
Sum of Cost	-8911.12	-9435.46	-9093.58	-8791.49	-8911.12	-10454.04	-10026.61	-10759.48	-8911.12	-9773.15	-9416.25	-9274.01	-8911.12	-11299.89	-10719.02	-11242.26
Sum of NB	0.00	1525.99	2512.61	4769.26	0.00	-113.88	969.51	511.62	0.00	948.09	1992.82	3861.20	0.00	-1795.22	-434.38	-436.96

Figure 4.9: Intervention Benefit & Cost in different collaboration team in collaboration scenario 4



	Overall				Traditional team				BIM				BSP			
	Intervention 1	Intervention 2	Intervention 3	Intervention 4	Intervention 1	Intervention 2	Intervention 3	Intervention 4	Intervention 1	Intervention 2	Intervention 3	Intervention 4	Intervention 1	Intervention 2	Intervention 3	Intervention 4
Sum of Benefit	13560.75	11271.10	13135.21	10805.30	11251.90	10283.45	11037.16	9870.36	993.24	329.83	877.07	272.48	1315.61	657.81	1220.98	662.46
Sum of Cost	-8791.49	-10759.48	-9274.01	-11242.26	-8989.05	-9970.31	-9259.94	-10387.61	13.31	-501.44	-96.26	-572.54	184.25	-287.73	82.19	-282.10
Sum of NB	4769.26	511.62	3861.20	-436.96	2262.85	313.15	1777.22	-517.25	1006.55	-171.61	780.81	-300.06	1499.86	370.08	1303.17	380.36

Figure 4.10: Comparison of Shapley value for different actors in game in collaboration scenario 4

4.5.3. Effectiveness of each intervention in difference scenario

Figure 4.11 highlights the effectiveness of different interventions in various collaboration scenarios. The findings emphasize the increasing NB with larger collaboration teams and more complex collaboration tasks.

Intervention 1 consistently demonstrates an increasing trend in NB. This could be explained by considering two factors of the intervention. Firstly, all intervention aims at overcoming the BIM barriers in the organization context, the effectiveness of invention benefits all involved department in the scenario; therefore, the increasing productivity of larger cooperation is higher than that of the small cooperation. Secondly, in all four studied scenarios, the collaborative workflow between various departments is linear in nature i.e. the output from the previous department is the input of next department; hence, the reduction in time consumed to finish that task is further magnified down the line of work process. This also highlights the effectiveness of having a group of specialists dedicated to integrating and aligning workflows between departments. As the scale of collaboration tasks increases, the impact of this intervention becomes more significant, resulting in higher NB.

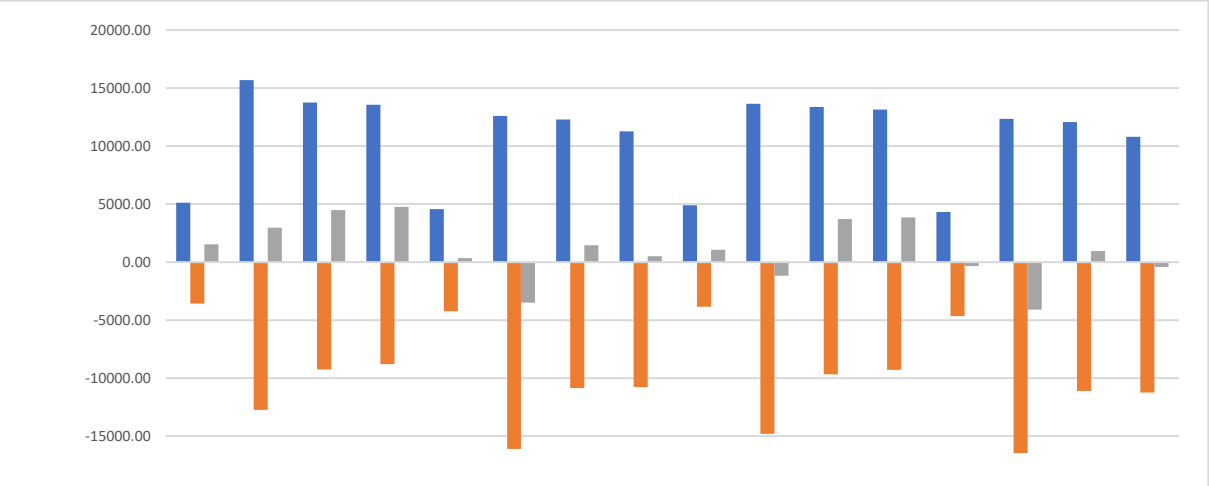
Intervention 3 also shows an increasing trend in NB, although with smaller values compared to Intervention 1. This suggests that in-house software development has a greater effect in more complex collaboration settings. However, in scenarios where the tasks can be completed using available software, the NB of this intervention becomes less attractive due to the increasing costs associated with its implementation.

Intervention 2 exhibits varying NB values among the different scenarios. Scenario 3 demonstrates the most positive NB, followed by scenario 4 and scenario 1. However, scenario 2 shows a negative NB. This indicates that additional training has some effect on collaboration, but its impact is not stable. Without clear work procedures mandating collaboration practices among departments, the effect of additional training tends to fade quickly, with departments reverting to relying on more capable dedicated staff or reverting to traditional work methods.

Similarly, the NB of Intervention 4 also varies among scenarios. Scenario 3 yields the most positive NB, followed by scenario 1. However, both scenario 2 and scenario 4 have negative NB values. This suggests that additional budget allocation for BIM facilities has an unstable

effect in different collaboration settings since it does not systematically mandate how different departments collaborate.

In summary, interventions focusing on integration, in-house software development, and training can yield positive NB, but their effectiveness may vary depending on the specific collaboration setting and the presence of clear collaboration procedures.



	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4
	Intervention 1				Intervention 2				Intervention 3				Intervention 4			
Sum of Benefit	5122.51	15693.35	13741.90	13560.75	4564.11	12590.72	12301.50	11271.10	4903.77	13643.40	13371.76	13135.21	4305.03	12337.63	12056.62	10805.30
Sum of Cost	-3576.66	-12717.9	-9264.91	-8791.49	-4223.60	-16092.3	-10843.0	-10759.4	-3835.46	-14808.8	-9670.54	-9274.01	-4650.86	-16439.8	-11099.6	-11242.2
Sum of NB	1545.85	2975.39	4477.00	4769.26	340.51	-3501.61	1458.50	511.62	1068.31	-1165.49	3701.22	3861.20	-345.84	-4102.23	956.95	-436.96

Figure 4.11: Net benefit of each intervention in difference collaborating procedure

4.5.3. Case study

The case study examines two ongoing mixed development projects within the same company, involving commercial, office, and residential sectors. As stipulated by the clients, these large-scale and complex projects require Integrated Digital Delivery for both the design and construction phases. Project A began two years prior to Project B. The data for the study were gathered through personal interviews with the BIM Managers of both projects, enabling them to provide detailed insights into the implementation activities. Additionally, information on BIM practices was obtained from past project documents. The focus of collaboration in both case studies is project cashflow monitoring and control.

4.5.3.1. Project A

In Project A, the client made it a contractual requirement to use BIM for Project cashflow monitoring and control, marking one of the earliest projects where this concept was mandated. Although the client included this requirement in the contract, both the client and contractors had limited practical experience in utilizing BIM for Project cashflow monitoring and control. The contractor conducted internal studies on the matter but lacked actual use cases.

At the project's outset, the BIM department, planning department, and QS department held several meetings to discuss the practical procedures and collaborative processes for implementing BIM in Project cashflow monitoring and control. Initially, the planning and QS departments shared their previous methods, which involved three key steps. Firstly, the

planning engineers would collect site progress information. Secondly, they would then proceed to translate this information into PDF mark-up plans. Finally, the mark-up plans would be transferred to the QS department, where they would be utilized for manual quantity take-off. Additionally, the same mark-up plans would also serve the purpose of obtaining client field staff certification.

Subsequently, the BIM department presented the conceptual framework for applying BIM to Project cashflow monitoring and control. Both the planning and QS departments provided their perspectives on the feasibility of this framework. This process continued until all three departments clearly understood their roles and responsibilities within the overall process. Additionally, a designated BIM specialist was appointed to facilitate coordination and collaboration between the departments.

Once the conceptual framework was established, the technical details of each sub-task within the overall procedure were sorted out between the three departments. This included construction method and construction zone planning, the method for planning engineers to update progress information in the BIM model, standard presentation formats for mark-up plans, methods for dividing the overall quantity according to the QS's cost structure, creating a code system to match model elements with progress information from the engineers and cost information from the QS, and methods for extracting quantities. All these details were aligned and agreed upon by all departments prior to project commencement. The detailed framework was approved by the client.

In addition to cross-department meetings and discussions, training programs for BIM software were conducted for the planning and QS departments. Furthermore, new software and higher specification laptops were provided to both departments. The training aimed to reduce the learning curve for both departments and enabled them to view the model and adjust element parameters without relying on complex BIM modeling tools like Revit.

After six months from the project's start date, an in-house web application was launched to enhance the collaboration process among the three departments. The web application allowed all departments to access the progress model, provide input, and extract output independently. Prior to the application, the collaboration process was mostly linear, but with the web application, some tasks could be carried out concurrently, reducing the engineering time required for Project cashflow monitoring and control.

4.5.3.2. Project B

In Project B, although the client did not explicitly mention the use of BIM in Project cashflow monitoring and control, the project director recognized the potential benefits and decided to apply this solution based on lessons learned from Project A. After the contract was awarded, training programs were initiated for the planning and QS departments to familiarize them with the software and processes involved in their tasks. Similar to Project A, the same laptop and desktop specifications were provided to the teams. The collaboration process and information exchange from Project A were also implemented in Project B, and the in-house software developed for Project A was scaled up and adopted for Project B. The project team received training on the operation and usage of this in-house software.

However, in Project B, instead of appointing specific staff members to handle collaboration and coordination between departments, a project BIM manager was deemed sufficient since the collaborative process was already well-established, and all the involved departments had received training.

During the implementation of BIM in Project cashflow monitoring and control, the project teams became increasingly reliant on the BIM managers for their tasks. Planning engineers started providing hand-drawn mark-up plans to the BIM team for progress updates in the model, deviating from the agreed-upon process, and QS personnel began requesting quantities from the BIM team instead of extracting them themselves using the software. Over time, the workload for the BIM manager increased due to the growing completed work as the project progressed. Eventually, the project team collectively agreed to discontinue the use of BIM in Project cashflow monitoring and control and revert to the traditional method.

4.5.3.3. Assessment

The characteristics of 2 cases is summarized in Table 4.9

Table 4.9: Summary of case characteristics

	Project A	Project B
Description	Large-scale and complex project Mandated of IDD by client BIM for project cashflow is part of contractual requirement	Large-scale and complex project Mandated of IDD by client BIM for project cashflow is not part of contractual requirement; however, project team support to implement it
Commencement year	2019	2021
Collaboration process	Dedicated specialist for collaboration No previously established workflow, all involved department collaborated to established procedure	No dedicated specialist appointed, BIM Manager also in-charge of collaboration Established workflow and lesson learnt from previous project available
In-house software	Yes, 6 months after commencement	Yes, available from project start
Training	Yes, involved all departments	Yes, involved all departments
BIM Facilities	Yes, BIM laptop and BIM software for involved department	Yes, BIM laptop and BIM software for involved department
Result	BIM implementation for Project cashflow sustained	BIM implementation for Project cashflow discontinued Other departments relied on BIM manager Revert to traditional workflow

Both Project A and Project B had similar characteristics, as they applied the same solution, process, software, and hardware. Additionally, both projects received the same training. However, Project A achieved better BIM implementation performance than Project B for a few key reasons.

Firstly, Project A had the advantage of a specialist appointed to facilitate department collaboration. This specialist successfully aligned and stipulated the work of other departments according to the agreed-upon procedure. This coordination and alignment were crucial in ensuring a smooth implementation of BIM in Project cashflow monitoring and control.

Secondly, in Project A, the requirement for the use of BIM in Project cashflow monitoring and control was mandated in the contractual agreement. This provided a strong directive for all parties involved, emphasizing the importance of BIM adoption in this particular aspect of the project. In contrast, Project B did not have this contractual requirement, potentially leading to a lower level of commitment and dedication to BIM implementation.

The case study highlights the significance of having a skilled specialist who can effectively collaborate and coordinate efforts across different departments, even in cases where a well-established process and lessons learned are already in place. While procedures can outline the overall framework, it is the responsibility of the specialist to align and bridge the differences in work processes among various departments. Each construction project is unique, with different team compositions and dynamics, requiring adaptability and problem-solving skills from the specialist.

The case study also underscores the importance of adequately utilizing in-house software. While the in-house software proved very useful in Project A, its efficiency was not fully utilized in Project B due to poor collaboration processes. This emphasizes that additional training, software, and hardware investments alone are insufficient to guarantee successful BIM adoption. Effective collaboration and communication are critical to harness the full potential of BIM tools and technologies.

Furthermore, the case study reveals that when a solution proves ineffective, other departments rely more on the BIM department to complete tasks or, in some cases, revert to traditional processes. This highlights the significant influence of traditional departments within the collaborating team and the supporting role of the BIM department. When designing solutions to overcome barriers in BIM adoption, it is crucial to consider the dynamics and relationships among different departments and address their specific needs and concerns.

In conclusion, while Project A and Project B shared similarities regarding solution, process, software, and training, Project A demonstrated better BIM implementation performance. The case study emphasizes the importance of effective collaboration, the role of specialists in aligning departmental efforts, and the need to optimize the utilization of BIM tools and technologies within the project context.

4.5.4. Summary

In analyzing the effectiveness of interventions in increasing work value across the four scenarios, it becomes evident that the cost of implementation significantly impacts the overall effectiveness in terms of net benefit (NB).

Intervention 1 consistently demonstrates the highest effectiveness and positive NB in all scenarios. This intervention establishes a grand coalition among departments, resulting in the

highest benefit for all players involved. Due to this intervention's stable and mutually beneficial nature, it is considered the most effective solution. The case study emphasizes the crucial role of a skilled specialist in effectively coordinating and collaborating across departments, adapting to unique project requirements and bridging work process differences.

Intervention 3 is the second most effective intervention, with positive NB in three out of four scenarios. However, in scenario 2, its effectiveness diminishes as players tend to break the grand coalition and either rely on more capable dedicated staff (scenario 1) or revert to traditional work methods (scenario 2). Despite this instability, Intervention 3 still showcases considerable effectiveness overall. The case study highlights the need for optimal utilization of in-house software, as demonstrated in Project A. It emphasizes that successful BIM adoption requires effective collaboration and communication, surpassing the mere reliance on training and investments in software and hardware.

Intervention 2 holds the third position in effectiveness, with positive NB in three scenarios, except for scenario 2. It also needs to improve on the same challenges as Intervention 3, where players are prone to breaking the grand coalition and resorting to more capable BIM staff or traditional work methods.

Intervention 4 emerges as the least effective intervention in all scenarios. It exhibits positive NB in only two scenarios: scenario 1 and scenario 3. This intervention lacks stability, as players tend to break the grand coalition and either rely on more capable BIM staff (scenario 4) or revert to traditional work methods (scenario 1 and scenario 2).

Overall, while all interventions prove effective in increasing work value across the scenarios, the cost of implementation and the stability of the grand coalition significantly impact their overall effectiveness in terms of NB. Intervention 1, which establishes a stable grand coalition, consistently demonstrates the highest effectiveness. Interventions 3 and 2 follow, albeit with less stability. Lastly, Intervention 4 ranks as the least effective intervention with its limited positive NB and lack of stability.

5. Discussion

The information obtained from data analysis presented in previous chapter is discussed to summarize key research findings. Section 5.1 is dedicated to examining the company's maturity level in BIM. Section 5.2 focuses on identifying the key actors involved in the BIM process. In Section 5.3, the barriers encountered are discussed. The design of interventions is discussed in detail in Section 5.4, while Section 5.5 delves into an evaluation of the effectiveness of these interventions using game theory. Lastly, Section 5.6 provides an in-depth exploration of the findings' validity, generalizability and limitation.

5.1. Current BIM Maturity Level

The BIM maturity level of the organization shown to be managed and partially defined under the framework proposed by Siebelink (2017) which was primarily designed for the Dutch construction industry. However, it was found that many of the criteria in this framework were also applicable to studies conducted in the Singapore context. It is important to note that there is currently no comparable Singaporean framework specifically designed for evaluating the BIM maturity of organizations. The most recent study in 2020 that focused on BIM maturity level was primarily aimed at assessing the performance of construction projects. This approach may not be ideal for determining the BIM maturity of a firm because different firms collaborate on a single construction project, and their BIM capabilities may vary significantly. Additionally, within a single firm, there may be variations in the prioritization of BIM resource allocation, making the performance of one project only partially representative of the overall BIM capabilities of the company.

The BIM maturity level of the company is relatively higher than that of the study by Siebelink (2017), evaluating the BIM maturity level of 32 engineering firms in 2016. It is expected since the BIM maturity level of engineering firms has evolved over the past five years. Therefore, it is reasonable to conclude that the BIM maturity of the company level is on par with the industry standard.

The organization's BIM maturity assessment reveals a mixed picture. While categories such as Strategy, People and Culture, and ICT Infrastructure have received higher scores than the organization's average, there are areas that require improvement. Organizational Structure, BIM Processes, and Data Structure have all received lower scores, indicating the need for enhancement in these areas. The organization's management is supportive of BIM implementation and has invested significantly in facilities and infrastructure. However, there is a lack of framework and procedures for manpower, process, and data management, which hinders progress. This is also evident from the highlighted barriers identified by various departments. To address these shortcomings, all departments agree that changes are necessary in the organization's structure. The formulation of a collaboration specialist group is proposed to overcome departmental silos and align process differences. Among all the categories, the Data Structure category has the lowest score. This can be attributed to several reasons. The existing system of object library and attributes is outdated and poorly managed. New BIM objects are added to the system without proper standardization, making it challenging to maintain organizational data standards. Additionally, while project-specific

processes and workflows are established in BIM execution plans, there is limited standardization at the organizational level. The success of BIM implementation largely depends on the proficiency of individual BIM managers for each project.

The BIM maturity level of each department within an organization was found to be dependent on their level of familiarity and experience with BIM. Departments with extensive experience and involvement in a larger number of BIM projects generally had a higher perception of BIM maturity. Conversely, departments with limited experience and involvement in fewer BIM projects tended to have a lower perception of BIM maturity. Interestingly, the departments responsible for planning and quantity surveying (QS) had an average perceived BIM maturity level. However, they highlighted a larger number of barriers during the interviews. This could be attributed to the nature of their work, which involves collecting and managing information from multiple sources. As other departments utilize their outputs, any loss or mismatch of information during collaboration can significantly impact their work, leading to increased barriers and challenges in achieving higher BIM maturity levels.

5.2. Important Actors in BIM Process

It was crucial to identify the significant actors involved to understand the barriers faced by different actors in the BIM implementation process within contractor firms. While many sources primarily focus on construction coordination and documentation, this study identified important actors and four typical collaboration scenarios that align with the Singapore government's initiatives for advanced BIM application and integrated project delivery, namely: Construction planning & scheduling, Cost planning & cost control, Progress monitoring, Progress update & claims. The study reveals that the company is aware of the industry's BIM development level and has aligned its capabilities accordingly, particularly in advanced BIM applications. This indicates a proactive approach towards adapting to industry advancements. Moreover, there is a high level of collaboration effort to break down department silos and promote collaboration and data exchange among departments. This collaborative approach is geared towards enhancing company productivity. Furthermore, the study highlights a substantial investment in manpower, hardware, software, and data structures to enhance the company's BIM capabilities. This investment underscores the company's commitment to leveraging BIM technologies and tools to improve overall performance and efficiency.

5.3. Barriers in BIM Implementation

This thesis breaks new ground by investigating barriers to Building Information Modeling (BIM) implementation with a diverse set of actors, in contrast to contemporary research. Previous studies have typically focused on technical disciplines, the BIM actor group, and project teams, or examined BIM barriers in collaborations between different companies within a single construction project. However, this thesis takes a different approach, as the identified barriers are not dependent on the BIM maturity of the studied actors but rather on their specific functions and work processes. Furthermore, some barriers are highly specific to the requirements and concerns when collaborating with specific departments.

Three of the four prominent barriers identified in this study have been previously highlighted in existing research. The difference in background knowledge, for instance, has been

addressed in studies conducted by Turk (2016), Enshassi and Abuhamra (2017), and Juan et al. (2017). These studies have indicated that barriers arise due to the lack of technical knowledge among BIM modelers, unfamiliarity with BIM standards and technologies, and a shortage of relevant BIM expertise and experience. Similarly, the high costs associated with BIM software and hardware have been highlighted by Juan et al (2017) in their research. They pointed out the financial challenges associated with investing in BIM hardware and software, as well as the technical difficulties related to multi-disciplinary integration and multi-user access to models. The limitation of current software to adapt to local workflows has also been acknowledged in previous studies conducted by Kiani et al. (2015) and Tan et al. (2019). These studies emphasized the increasing need for specialized software and the lack of domestically oriented BIM tools, further supporting the barriers identified in this thesis.

While previous research has touched on the resistance to BIM adoption by departments and the challenges of integration, they primarily focused on corporate culture, industry conservatism, and technical integration challenges. In contrast, this thesis, as highlighted in section 4.3, reveals that the leading cause of integration and collaboration issues between departments is the difference in workflow among each department. This discrepancy leads to higher stress levels, time pressure, steep learning curves, communication problems, and resistance to adopting new technologies. Although studies by Juan et al. (2017) and Khosrowshahi and Arayici (2012) did touch on some aspects of this issue, such as industry conservatism, resistance to change, and difficulties in multi-disciplinary and construction-level integration, they did not emphasize the specific challenges arising from workflow misalignment. As demonstrated in section 4.3, this thesis highlights the profound impact of workflow differences on integration and collaboration barriers, including heightened stress levels, time pressure, steep learning curves, communication issues, and resistance to technology adoption

In addition to the 4 prominent barriers identified in this study, there are also other less prominent barriers that have been highlighted in previous research. For example, Chelson (2010) pointed out the difficulty in engaging field staff, specifically their dislike of BIM coordination meetings. Similarly, Oesterreich and Teuteberg (2016) emphasized data security and protection concerns, highlighting the potential risk of data breaches.

However, this study did not find support for some of the other prominent barriers highlighted in previous research. For instance, Bernstein et al. (2012) identified resistance to changes in corporate culture and structure, as well as a lack of understanding by executives about the value of BIM processes. In the case of the company studied in this thesis, these barriers were absent due to the company's realization of the benefits of BIM and its implementation efforts since 2011. The company has invested in BIM hardware and equipment, recruited qualified BIM personnel, and upskilled existing employees. Additionally, the company's involvement in government projects, which advocate for BIM implementation and make it compulsory, has contributed to a positive BIM adoption environment. However, it is important to note that these barriers may still be relevant for companies with smaller financial capacity and smaller project scales, where BIM implementation may face more challenges. Similarly, the need for key stakeholders to agree on information exchange and the shortage of skilled employees in

BIM, as highlighted by Azhar et al. (2014), may be less prominent in the context of intra-organization BIM implementation. These issues are more relevant at the management level of the company and are often associated with collaboration with external stakeholders. Since this study focused on BIM implementation within a single company, where collaboration is primarily internal, these barriers were not as significant. Furthermore, insufficient evidence supporting the benefits of BIM and interoperability issues due to software selection and insufficient standards, as identified by Kent and Becerik-Gerber (2010), were not major barriers in this study. The company under investigation had a relatively high BIM maturity, implemented BIM for multiple projects and perceiving its benefits based on extensive experience. As a result, software selection had been refined, and the interoperability issues typically associated with different software platforms were not prominent within the company's internal BIM collaboration framework.

In summary, the thesis contributes to exploring BIM barriers from a different perspective compared to previous research. Three out of the four prominent barriers have been previously highlighted: differences in background knowledge, high costs of software and hardware, and limitations of current software to adapt to local workflows. The resistance of BIM adoption by departments due to workflow misalignment is partially addressed in previous studies. Still, this thesis emphasizes its impact on stress levels, time pressure, learning curves, communication, and resistance to new technology. Less prominent barriers, such as difficulty engaging field staff and concerns about data security, have also been recognized. However, barriers related to resistance to changes in corporate culture, lack of executive understanding, stakeholder agreement on information exchange, shortage of skilled employees, insufficient evidence supporting BIM benefits, and interoperability issues were not significant in this study. These differences can be attributed to the specific context and characteristics of the company studied, including its high BIM maturity, financial capacity, project scale, and focus on intra-organization BIM implementation.

5.4. Proposed Intervention

The proposed interventions to lower the barriers in BIM adoption align with solutions mentioned in previous studies. The intervention of developing in-house software corresponds to the solution of promoting research and development in BIM technologies, as suggested by Chan et al. (2017). This highlights the importance of customized software solutions to meet specific organizational needs and improve workflow efficiency. Similarly, the intervention of creating training programs and knowledge sharing sessions is similar to the solution proposed by Blayse and Manley (2004) regarding the development of a BIM framework and the training recommendation by Smith (2014). These interventions aim to enhance the knowledge and skills of staff members, fostering a common understanding and facilitating effective collaboration.

The intervention of allocating additional budget for BIM facilities is also emphasized in the study conducted by Chan et al. (2017), which recommends financial incentives and monetary subsidies from the government to encourage firms involved in BIM projects. This highlights the importance of adequate financial resources for acquiring the necessary hardware and software infrastructure, ultimately supporting the successful implementation of BIM.

Regarding the formulation of a group of specialists, the concept is partially mentioned in previous studies. Smith (2014) emphasizes the need for effective communication between key stakeholders, while Blayse and Manley (2004) suggest hiring or engaging professionals skilled in BIM. However, neither of these studies explicitly addresses this group's objective, which is to facilitate collaboration between departments by aligning differences in procedures and workflows. This intervention recognizes the significance of having dedicated specialists who can act as facilitators, advisors, and trainers, bridging the gap between different backgrounds and ensuring smooth integration and understanding throughout the organization.

In summary, the interventions proposed to address the barriers in BIM adoption align with solutions mentioned in previous studies. These include developing in-house software, creating training programs and knowledge sharing sessions, allocating additional budget for BIM facilities, and formulating a group of specialists. By drawing on the insights and recommendations from prior research, these interventions aim to overcome the identified barriers and promote successful BIM implementation within the organization.

5.5. Effectiveness of Intervention

Overcoming barriers to Building Information Modeling (BIM) implementation is crucial for organizations seeking to maximize the benefits of this technology. While previous studies have primarily focused on identifying barriers and recommending solutions, this thesis breaks new ground by examining interventions' effectiveness in terms of benefits and costs. By maintaining consistent team composition, work procedures, and software usage across interventions, the reduction in engineering time becomes the primary measure of intervention effectiveness.

The findings of this thesis indicate that all interventions positively impact increasing work value by decreasing engineering time, although the level of benefits varies among interventions. However, what sets these interventions apart is the cost associated with their implementation. This echoes previous studies highlighting the cost-related barriers in BIM implementation, such as high implementation and maintenance costs, insufficient evidence supporting the benefits of BIM, reluctance to invest in training due to costs and potential productivity loss, and high costs associated with BIM hardware and software (Juan et al., 2017) .

The low effectiveness of intervention 2, which involves additional training, and intervention 4, which entails an additional budget for BIM facilities, further validates the findings of previous studies. It demonstrates that additional investment in training or BIM facilities does not always effectively reduce barriers. While these interventions enhance overall productivity, the benefits they generate are not significant enough to offset the associated costs. Moreover, the effectiveness of these interventions varies across collaboration scenarios, and they do not have a magnifying effect as tasks become more complex.

On the other hand, the high effectiveness of intervention 1, which focuses on forming a group of specialists, and intervention 3, which involves the development of in-house software, highlights the importance of aligning work procedures between departments and reducing the learning curve for non-BIM staff. These interventions facilitate comprehensive

collaboration between BIM and other departments, garnering more support and reducing resistance to adopting the BIM workflow. As these interventions primarily impact workflow and collaboration procedures, their effectiveness increases as the complexity of collaboration tasks and team size grows.

The stability of interventions in different scenarios carries significant implications. The grand coalition consisting of the traditional team, BIM staff, and BSP staff tends to be unstable if the intervention is ineffective. In such cases, teams may revert to the traditional workflow without adopting BIM, resulting in poor returns on the company's investment in BIM. Even after training, reluctance to use new technology has been previously highlighted (Juan et al., 2017).

Alternatively, teams may rely heavily on more experienced and capable BSP staff. While collaboration between the BIM department and other departments still occurs in this scenario, it is unfavorable for the company for two reasons. Firstly, maintaining a large team of experienced manpower leads to suboptimal utilization since collaboration scenarios in this thesis occur infrequently. Secondly, although BSP staff may excel in modeling-related work, their specialty lies in collaborating and coordinating efforts across different departments, making them less than ideal substitutes for BIM staff. Therefore, from the company's perspective, the optimal team composition is a grand coalition that includes a mix of BIM and BSP staff. This composition balances the abilities of both teams while considering the cost of maintaining the team.

Cooperative game theory and the Shapley value solution concept provide valuable insights into the contribution and influence of each player in collaborative teams and allow for the simulation of strategic decisions in different scenarios. By analyzing the distribution of benefits and costs, these frameworks help reveal the dynamics of collaboration and decision-making among stakeholders in the BIM process.

Applying non-cooperative game theory to BIM implementation may not be suitable due to its underlying assumption of opposing interests among players. In the case of BIM, the implementation is mandated company-wide, and the organization has already made significant investments in hardware, software, manpower, and equipment. Therefore, departments have a strong incentive to collaborate and work towards achieving higher collective pay-offs. Non-cooperative game theory may promote individualism and isolated working environments, which can hinder the effective adoption of BIM and the realization of its benefits.

Although known for its stability problem, the Shapley value solution concept is highly relevant in this thesis. While the Shapley value provides a unique solution for the allocation problem, it does not guarantee the stability of cooperation. However, this instability feature of the Shapley value is valuable for analyzing the stability of different interventions in various scenarios. It allows for an understanding of how different interventions affect the cooperative dynamics within collaborative teams and whether the collaborations are likely to persist over time.

Cooperative game theory and the Shapley value solution concept provide a more comprehensive and realistic approach to analyzing the dynamics and interactions among

stakeholders in the BIM process. It considers the cooperative nature of BIM implementation and the shared interests of the players involved. By incorporating these frameworks into the analysis, this thesis gains a deeper understanding of the effectiveness of interventions and their impact on collaboration, productivity, and the overall success of BIM implementation.

The effectiveness of each intervention in reducing barriers and promoting the use of BIM within the firm varies, but all interventions have a relatively positive impact. Additionally, each intervention enhances the BIM maturity of the firm in different aspects, contributing to the overall advancement of BIM implementation.

Intervention 1, which involves the formation of a group of specialists, primarily focuses on increasing the Building Information Modeling (BIM) maturity level in the category of BIM processes. This intervention recognizes the importance of a more comprehensive and integrated approach to BIM implementation by aligning and integrating different processes used by various departments within the organization. By bringing together specialists with expertise in BIM methodologies, standards, and workflows, this group acts as a catalyst for change and drives the adoption of advanced BIM applications. Through their knowledge and experience, these internal actors not only advocate for the use of BIM but also play a crucial role in fostering a culture of BIM adoption within the organization. Their expertise and ability to demonstrate the benefits of BIM to different departments and stakeholders contribute to the advancement of BIM maturity in the category of people and culture. By promoting awareness, providing guidance, and sharing best practices, they help instill a mindset that values BIM as a transformative tool for project delivery and collaboration. Furthermore, the formation of this specialist group also contributes to BIM maturity in the data structure category. By facilitating the integration of processes and establishing synchronized data exchange protocols and information structures, they enhance the overall data management practices within the organization. Through their efforts, data consistency, integrity, and accessibility are improved, allowing for more efficient information sharing and decision-making processes.

Intervention 2 complements the first intervention by focusing on additional training and knowledge-sharing initiatives. This intervention directly contributes to BIM maturity in the category of people and culture as well as BIM process. By increasing motivation for change, supporting education and training programs, and promoting cooperation, openness, and transparency, this intervention aims to foster a more BIM-oriented culture within the organization. By investing in continuous learning and professional development opportunities, employees gain the necessary skills and knowledge to effectively utilize BIM tools and workflows. This not only improves their individual competencies but also strengthens the overall capacity of the organization to implement BIM successfully. Additionally, knowledge-sharing activities such as workshops, seminars, and mentoring programs create an ecosystem for process change and improvement. Employees are encouraged to share their experiences, lessons learned, and innovative ideas, resulting in a more collaborative and innovative work environment.

Intervention 3 involves the development of in-house software tailored to the specific needs and requirements of the organization's BIM implementation. This intervention directly targets

an increase in BIM maturity in the categories of ICT infrastructure and data structure. By developing custom software solutions, the organization can address specific challenges and optimize BIM workflows to enhance efficiency and effectiveness. The in-house software can provide specialized functionalities, automated processes, and streamlined workflows, thereby improving the overall BIM capabilities of the organization. It facilitates seamless integration with existing software systems, data exchange platforms, and project management tools, ensuring smooth collaboration and data interoperability. Furthermore, the development of in-house software allows for the creation of object libraries and data templates that align with industry standards, enabling consistent data structuring and information management practices.

Intervention 4 involves allocating an additional budget for BIM facilities, further reinforcing the organization's commitment to advancing BIM maturity in the categories of ICT infrastructure and data structure. By investing in the necessary hardware, software, and infrastructure, the organization creates an environment conducive to efficient BIM implementation. The additional budget allows for the acquisition of high-performance workstations, advanced software licenses, and networking infrastructure that can handle the demands of BIM projects. Upgrading the hardware and software capabilities ensures that employees have access to the necessary tools and resources to effectively execute BIM processes and workflows. Moreover, the allocation of a budget for BIM facilities enables the organization to implement state-of-the-art data storage and backup systems, ensuring data security, accessibility, and long-term availability.

Collectively, these interventions contribute to the overall advancement of BIM maturity within the firm by addressing key aspects such as organizational structure, people and culture, BIM process, ICT infrastructure, and data structure. By focusing on these areas, the firm can enhance its BIM capabilities and achieve higher levels of productivity, collaboration, and effectiveness in the use of BIM technology. The combination of these interventions creates a comprehensive approach to overcoming barriers and fostering a more mature BIM implementation within the organization.

5.6. Generalizability

This thesis consists of five key parts: BIM maturity level of organizations, key actors involved in BIM implementation, barriers experienced by these actors, proposed interventions to overcome the barriers, and the evaluation of intervention effectiveness.

Regarding the BIM maturity part, the assessment of an organization's BIM maturity level is specific to the studied company. However, the assessment framework developed by Siebelink could be adopted by other construction firms in Singapore to evaluate their own BIM maturity levels, takes into account comprehensive factors in BIM implementation, including technology, processes, people, and organization. Currently, there has yet to be a published framework specifically developed for the Singapore market. While the Building and Construction Authority (BCA) recognizes firms with high levels of BIM implementation, this serves more as a means to acknowledge top players in the industry rather than a structured, formalized assessment tool for BIM maturity.

The barriers identified in this thesis have largely been mentioned in previous studies, suggesting that other similar firms have experienced similar sets of barriers during BIM implementation. Moreover, comparing the contextual factors of actors involved in the BIM process from previous studies, the barriers they encounter are relatively similar, indicating that the barriers are not different based on the BIM maturity of the firm or the nature of the company itself, but rather on the roles and responsibilities of the actors involved. Although there are differences in the barriers experienced by different actors, the majority of the described barriers are common. However, some prominent barriers, such as a lack of top management support for BIM implementation, were not found in this study. It is recommended that other firms thoroughly investigate their own implementation status before applying similar interventions.

Similarly, the proposed interventions identified in this thesis largely align with previous studies. Therefore, these proposed interventions can be applied by other similar firms, taking into account their BIM capabilities and available resources. Among the four interventions evaluated, allocating additional budget for BIM facilities and providing additional training had the least impact on overcoming BIM barriers, as the benefits when implementing these interventions did not reliably surpass the additional costs. This finding aligns with previous studies that highlight firms' resistance to implementing BIM due to insufficient evidence supporting its benefits or the belief that implementation and maintenance costs outweigh the financial benefits. On the other hand, the interventions of forming specialist groups for collaboration and integration and developing in-house software emphasize the importance of aligning different department workflows and procedures and reducing the learning curve and complexity of adopting new technology into existing workflows. Both of these solutions directly aim to reduce resistance from traditional teams in adopting BIM as a new innovative process, and they have already proven their effectiveness in enhancing the benefits of BIM, where the additional productivity gains outweigh the investment. The effectiveness level of these interventions can serve as a reference for other similar construction firms in developing their roadmap for BIM implementation. However, considering that the company studied had high management support for BIM and good financial capacity, the exact effectiveness may vary when applied to other construction firms.

In summary, this thesis provides valuable insights into BIM maturity, key actors, barriers, proposed interventions, and intervention effectiveness in the context of Singapore's construction industry. While the BIM maturity assessment is specific to each organization, the assessment framework developed by Siebelink can be utilized by other firms. The identified barriers and proposed interventions are similar to previous studies, suggesting their relevance to similar firms. However, it is crucial for firms to assess their specific implementation status and adapt the interventions accordingly. By considering these findings, construction firms can make informed decisions and develop effective strategies for successful BIM implementation.

6. Conclusion

The primary goal of this thesis was to identify interventions to address the barriers faced by significant actors during the implementation of BIM within large contractor firms in Singapore. This concluding chapter provides the conclusions related to the research question as outlined in Section 6.1. Furthermore, Section 6.2 offers a discussion on the scientific and practical relevance of the study. The limitations of the research are presented in Section 6.3, and finally, recommendations for future research are discussed in Section 6.4.

6.1. Answer to Research Question

This research focuses on enhancing the implementation of BIM in a large contractor firm in Singapore by identifying suitable strategies to overcome barriers to BIM implementation. The study is conducted within the specific context of the chosen contractor firm, taking into account its workflow, culture, technical expertise, and BIM maturity. The research question aims to uncover effective solutions for the barriers experienced in BIM adoption within the firm. The research objectives are to determine which solutions yield the best net benefit in addressing the barriers faced by actors within the contractor firm. Cooperative game theory is employed as a framework to simulate different scenarios with various interventions, allowing for the identification of the most suitable intervention. The research sub-questions focus on (1) assessing the current level of BIM capabilities within the organization, (2) identifying the actors involved in and benefiting from the BIM process, (3) understanding the barriers experienced by these actors, and (4) exploring the solutions to these difficulties and evaluating their effectiveness. By addressing these questions, the research aims to provide practical and effective strategies for enhancing BIM implementation in the contractor firm, thus contributing to the overall advancement of BIM implementation in the Singapore construction industry.

6.1.1. Current BIM Maturity of the organization

The study involved a total of 35 respondents from different departments within the organization. The majority of respondents were from the BIM department, followed by the QS, Planning, and Finance departments. Unsurprisingly, the BIM department had the highest familiarity and experience with BIM, as it is their primary area of expertise. The QS and Planning departments also had some familiarity and experience with BIM, albeit to a lesser extent, while the Finance department had limited exposure to BIM due to their late involvement in the overall adoption process.

The organization's BIM maturity scores were assessed across different categories and sub-categories. The overall average BIM maturity score for the organization was 3.21 on a scale of zero to five. The highest maturity score was in the category of ICT Infrastructure and Strategy, indicating that the company recognized the benefits of BIM and made investments in manpower and facilities. However, the lowest maturity score was in the category of Data Structure, suggesting a need for improvement in data organization and exchange quality.

When comparing departments, the BIM department had the highest overall BIM maturity, while the Finance department had the lowest. This correlation aligns with the previously observed familiarity patterns. It can be concluded that familiarity with BIM influences the

organization's awareness and maturity level in BIM implementation. However, the differences in maturity levels between departments were not significant.

6.1.2. Importance actors in BIM implementation within organizations

The implementation of Building Information Modeling (BIM) within the company involves key departments such as BIM, Planning, Quantity Surveying (QS), and Finance. These departments were identified through interviews and align with the literature on personnel involvement in the Singapore BIM process. The BIM department takes a central role in strategic planning and execution of BIM implementation, while also facilitating collaboration with other departments for 4D and 5D solutions. The Planning department focuses on construction planning and project monitoring, working closely with project leaders and supporting the QS department in progress claim and payment processes. The QS department manages the contractual framework, including tendering, subcontractor engagement, and project cash flow management. The Finance department handles overall financial aspects, including budgeting, reporting, risk management, and cash flow monitoring.

In terms of collaboration scenarios, four key tasks were identified that require close collaboration among the four departments. These tasks include project schedule monitoring and control, cost estimating and budgeting, project cash flow monitoring and control, and company cash flow monitoring and control. The study aims to investigate the barriers experienced by these departments in these specific scenarios and explore potential solutions to overcome these barriers. Overall, this research provides valuable insights into the roles, collaboration, and challenges faced by different departments in the implementation of BIM within the organization.

6.1.3. Barriers in BIM implementation

The implementation of Building Information Modeling (BIM) within the company revealed several common barriers experienced by different departments. These barriers were analyzed and organized based on their similarity, resulting in four prominent barriers that all departments highlighted.

The first common barrier is the need for aligning objectives and collaboration among different departments. Each department has its own established functions and protocols, which makes comprehensive implementation challenging and often requires multiple systems to operate concurrently. This lack of alignment creates resistance to change during the transition period, as it increases stress levels and time pressure.

The second barrier is related to the learning curve associated with digital tools and technologies. As these tools are relatively new to all participants, there was a drop in productivity at the beginning of the implementation process. Differences in background knowledge and expertise create communication gaps and reduce trust levels among departments, making mindset change a significant obstacle.

The third barrier is the lack of well-established and customized digital tools and technologies that align with local work practices. This leads to a substantial amount of time and cost spent on exploring and integrating these processes into the workflow.

The fourth barrier is the increased hardware and software specifications required to view digital models, due to the larger sizes of BIM models. This poses challenges in terms of investment and technological requirements.

While the QS, Finance and Planning departments mentioned additional barriers such as time pressure, engaging field staff, and the risk of security breaches, these were excluded from the study as they were specific to their respective departments and not encountered by the majority of stakeholders involved in the study.

This thesis provides a fresh perspective on BIM barriers, complementing previous research. It emphasizes the impact of workflow misalignment on stress levels, time pressure, learning curves, communication, and resistance to new technology. The study acknowledges less prominent barriers to engaging field staff and data security concerns. However, barriers associated with resistance to changes in corporate culture, lack of executive understanding, stakeholder agreement on information exchange, shortage of skilled employees, insufficient evidence supporting BIM benefits, and interoperability issues were not significant in this particular study. These differences can be attributed to the specific context and characteristics of the company studied, including its high BIM maturity, financial capacity, project scale, and focus on intra-organization BIM implementation.

6.1.4. Effectiveness of intervention in overcoming BIM barriers

The study identified four interventions that the involved departments commonly suggested to overcome the barriers in BIM implementation. The most frequently proposed intervention was forming a specialist group focused on collaboration and integration. This group would act as facilitators, bridging the gap between departments and providing guidance and training on BIM integration. It would help improve technical understanding and alleviate time pressure during the transition, reducing resistance to change. The second intervention involved establishing a training program and knowledge-sharing sessions among departments to enhance overall knowledge and understanding of BIM. The third and fourth interventions focused on developing in-house software and allocating additional budget for BIM facilities. This aimed to reduce the learning curve for non-BIM staff, integrate BIM into existing workflows, and enhance the ability to operate and extract data independently

These proposed interventions align with previous studies and can be applied by similar firms, considering their BIM capabilities and available resources. All four interventions were proved to be effective. However, it was found that allocating additional budget for BIM facilities and providing additional training had the least impact on overcoming barriers, as the benefits did not consistently outweigh the costs. This aligns with the concerns of firms regarding the costs and benefits of BIM implementation. On the other hand, the interventions of forming specialist groups and developing in-house software were effective in aligning workflows, reducing resistance, and enhancing the benefits of BIM. These solutions address the challenges of integrating BIM into traditional workflows and reducing the learning curve associated with new technology.

It is important to note that the effectiveness of these interventions may vary when applied to other construction firms, as the studied company had high management support and good

financial capacity for BIM. Nonetheless, the effectiveness level of these interventions can serve as a reference for other firms in their BIM implementation roadmap. Overall, the study contributes to the understanding of effective interventions to overcome barriers in BIM adoption and provides insights for firms seeking to enhance their BIM implementation strategies.

6.2. Scientific and Practical Relevance

6.2.1. Scientific Relevance

Previous literature has extensively discussed the benefits and barriers of BIM implementation, focusing primarily on BIM project-wide implementation rather than BIM implementation within a firm and the collaborative processes between internal departments. Moreover, these studies often present barriers in a general sense without considering the differences in barriers experienced by different actors. Therefore, this thesis makes a significant scientific contribution by exploring the barriers faced by various actors and revealing that these barriers are not dependent on the BIM maturity of the actors but on their roles and responsibilities within the organization.

Furthermore, this thesis goes beyond proposing interventions to overcome these barriers. It evaluates the effectiveness of these interventions in a collaborative setting between departments within the firm, shedding light on team dynamics within the collaboration scenario. By applying cooperative game theory, this study offers a novel approach to analyzing the BIM implementation problem in the context of Singapore. It demonstrates the applicability of game theory in understanding how different actors interact and contribute to the success of teamwork projects.

6.2.2. Practical Relevance

This study significantly contributes to the practical aspects of BIM implementation in the construction industry. Firstly, as the research is conducted within a large contractor in Singapore, the identified barriers and the proposed solutions provide valuable reference points for other contractors with similar BIM capabilities. Using the same method and framework employed in this study, other firms can evaluate their BIM maturity levels, identify barriers experienced by different departments within their organizations, and determine appropriate solutions to overcome them.

Secondly, the effectiveness of the proposed solutions serves as a guideline for strategic planning in BIM implementation for other construction firms. It provides insights for decision-making processes related to recruitment, training programs for existing staff, and understanding the expected outcomes when implementing specific interventions. This allows companies to make informed decisions and optimize their BIM implementation strategies.

Thirdly, the application of cooperative game theory in this study introduces a novel approach to BIM research. Despite its complexity, cooperative game theory proves to be a useful method for testing the effects of interventions. The concept of the Shapley value, which ensures a fair distribution of both costs and benefits, can be applied in various scenarios. For example, when multiple departments decide to invest in new BIM technology or develop in-

house software, the cost burden can be shared among the departments that benefit from the investment, rather than being solely borne by the BIM department.

Overall, this study provides practical insights and tools that can be utilized by construction firms to enhance their BIM implementation strategies, improve collaboration between departments, and allocate costs and benefits fairly and efficiently.

6.3. Limitation

It is important to acknowledge several limitations in this research. Firstly, the data collection was limited to a single contractor firm, which may restrict the generalizability of the findings to other contractor firms in Singapore or different countries. The focus on obtaining in-depth details from one firm limits the ability to draw broader conclusions about the industry as a whole. Additionally, it should be noted that data collected from different firms might yield slightly different results, highlighting the need for further investigation. Another limitation is that the research primarily focuses on actors directly using BIM and/or departments directly benefiting from its implementation. Other actors and departments indirectly involved in the BIM process are not extensively considered, leading to an incomplete understanding of the overall ecosystem and dynamics of BIM implementation within an organization or industry.

Furthermore, the application of game theory in this research simplifies the complex realities of BIM implementation. While game theory provides a useful framework for analyzing strategic interactions among actors, it may not fully capture the intricate relationships and dynamics among the various stakeholders involved in the BIM process. Moreover, the use of the Shapley value as a solution for the allocation problem may not guarantee the stability of cooperation, as the corresponding value may not lie in the core. This highlights the need to assess the implementability of cooperation within the context of BIM implementation.

In the context of BIM implementation in Singapore, the government plays a leading role by mandating BIM collaboration, which is supported by the management of companies and their significant investment in BIM implementation. These supports encourage collaboration between departments within these companies. However, it is important to recognize that these departments, despite cooperating, still pooling from the same company resource. Stated differently, both cooperation and competition coexist. This dynamic presents a realistic and challenging scenario for modelling and studying the interplay between competition and collaboration in BIM implementation.

Lastly, the geographical limitation of the data collected and analyzed in the Singapore context should be acknowledged when interpreting and generalizing the main findings of this study.

6.4. Recommendation for Future Research

The section presents several recommendations for future research in the field of Building Information Modeling (BIM). One suggestion is to apply cooperative game theory to analyze the collaboration between different companies in a BIM project, particularly in the context of Singapore where government developers require BIM implementation in contracts. This approach would help address the barrier of high upfront investment for smaller subcontractors by studying cost and risk sharing among project teams. By reducing the

financial burden on smaller companies, cooperative game theory could facilitate their participation in BIM projects and promote collaboration.

Furthermore, the study proposes exploring alternative solution concepts, such as the Nash bargaining solution, to complement the Shapley value used in this research. The Nash bargaining solution takes into account the presence of both cooperation and competition among actors, which is more realistic in practical settings. However, one potential challenge is the assumption of equal bargaining power among players. From this study, it is inferable that bargaining power of BIM department is significantly weaker than other department due to their supporting role. Future research could investigate ways to model the problem and consider power dynamics within the BIM collaboration framework.

Another research gap identified is the lack of a BIM maturity evaluation framework for organizations in Singapore. While current research focuses on evaluating BIM maturity at the project level, it is equally important for firms to assess their own maturity level and identify areas for improvement. Developing an evaluation framework specific to organizational BIM maturity would provide valuable insights for firms, guiding their investment decisions and prioritizing areas that offer the most potential for improvement.

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Appendix A: BIM Maturity of Organization

A.1. BIM Maturity Assessment Framework by Siebelink (2017)

Category	Description	Description maturity level					
Strategy	The vision and goals for BIM, how management supports them, and how experts and teams support BIM implementation.	0 – Not present	1 – Initial	2 – Managed	3 – Defined	4 – Quantitatively managed	5 - Optimized
BIM-vision and goals	A BIM-vision can be created and BIM-goals can be used to guide the BIM implementation process.	There is no vision or BIM goals.	There is a (basic) vision for BIM, but no concrete goals are associated with it.	Generic BIM goal are used. A BIM-vision is either missing or not aligned with the BIM-goals.	The BIM-vision aligns with the organizational vision/strategies and is tailored to close collaboration partners.	BIM vision and goal are defined SMART.	The BIM vision and goals are constantly monitored and adjusted as needed.
Management support	The extent to which management supports BIM implementation and development by providing budgets and explaining the importance of BIM.	Management provides no support for BIM.	BIM support is limited and unstructured. Budgets are made available on an as-needed basis.	The value of BIM is widely acknowledged, but budgets are limited.	BIM is supported by adequate/appropriate budgets.	Appropriate means are made available for the development of BIM and the implementation of new applications.	Support for a continuous effort to implement BIM and to ensure future BIM implementation.

BIM expertise	Depending on the size of the organization, a BIM expert, BIM team, and/or BIM-related department may be present. These frequently play a guiding, advising, and supporting role in BIM implementation.	There is no BIM expert, BIM team, or BIM-related department present.	A BIM expert with little time to devote to BIM initiatives. A BIM team or group of core users meets on an irregular basis to discuss BIM implementation.	BIM-expert(s) with adequate time/capacity for BIM implementation.	The BIM-expert collaborates closely with the relevant parts of the organization. A BIM-team or group of core users represents all (relevant) company parts.	Higher management is represented among the BIM expert(s) or BIM-team. There is close collaboration with parts/teams in charge of BIMtasks.	The expert/team's BIM-related discussion is taken into account in order to adjust the BIM strategy based on knowledge, experience, and developments.
Organisational structure	The formal composition of the organization, such as the hierarchical structure and job descriptions, is included in the organizational structure. The project structure describes how BIM tasks, responsibilities, and risks between project parties are documented.	0 – Not present	1 – Initial	2 – Managed	3 – Defined	4 – Quantitatively managed	5 - Optimized

Tasks and responsibilities	The extent to which tasks and responsibilities related to BIM processes are formalised and how prevalent they are in practice.	There is no documentation of tasks and responsibilities for BIM-related processes.	BIM tasks and responsibilities are either incompletely or inadequately documented.	BIM-process tasks and responsibilities are adequately documented, but only to a limited extent integrated into regular job descriptions.	BIM-process tasks and responsibilities are documented at the project level. For this, project teams use (standard) task and role descriptions.	Tasks and responsibilities are adjusted at the organizational level to remain accurate for current BIM use.	Documented BIM-related tasks and responsibilities are evaluated on a regular basis in order to keep them up to date in a changing environment.
Contractual aspects	The extent to which clear agreements about BIM are made with other parties. The emphasis is on agreements that are formalized through a contract, BIM-protocol, or other means.	Contracts, protocols, and other written agreements do not include BIM.	Depending on the project or project team, BIM is included in contracts or protocols. Within the organization, there is no standard for this.	The organization established clear guidelines for incorporating BIM into contracts or protocols, but these are rarely followed in practice.	Contracts or protocols with other parties explicitly document BIM collaboration. The organization can take the lead in formalizing this process.	BIM-related agreements are specific and measurable, and are documented in contracts or protocols: this clarifies which and when information must be delivered.	Changes in BIM usage, new insights into BIM, and potential changes in legal conditions are closely monitored in order to adjust contracts and protocols accordingly.
People and culture	People's and organizations' characteristics and competencies. Individual motivation or business culture, for example, can influence not only current BIM use, but also the	0 – Not present	1 – Initial	2 – Managed	3 – Defined	4 – Quantitatively managed	5 - Optimized

	transition to new work methods and technologies.						
Personal motivation and willingness to change	Personal drivers must accept and support the implementation of BIM. This motivation is driving people's willingness to adapt their working methods to BIM use. Personal factors also have a significant impact on the extent and speed with which organizational changes occur. Individual motivations can be greatly influenced by the current organizational culture.	People are hesitant to adopt BIM.	Personal factors influence whether or not BIM is used on a project level. The organization's culture is not conducive to the transition to BIM.	Despite top-level motivation and early adopters, the majority of the organization lacks enthusiasm for BIM.	Within the organization, there is a lot of enthusiasm for BIM. As a result, there is a greater willingness to change working practices in favor of BIM.	The current organizational culture encourages BIM implementation. Traditional job descriptions and processes are modified to accommodate BIM use.	The organization's strong motivation to improve and implement BIM allows it to quickly adapt to new BIM developments.

Requesting actor (internal)	A requesting actor contributes to the beginning of the BIM implementation process. This BIM champion guides and motivates others in the organization to use BIM.	There is no requesting actor (BIM champion) present.	A BIM champion is present, but this person lacks the time and resources to carry out this role effectively.	The BIM champion has limited time for his role, despite his ability to advance BIM.	The number of BIM champions present, as well as their backgrounds, are appropriate to support BIM-perspectives from various people, target groups, and departments.	A BIM champion is in the managing board. This individual is in close contact with those in charge of operational BIM tasks.	One or more BIM champions from the organization collaborate closely with BIM champions from other organizations.
Education, training and support	BIM education, training, and support include general organizational information as well as instruction and guidance for specific people/target groups. This results in the development of competencies for carrying out BIM-related tasks.	There is no BIM education or training available.	BIM education and training is haphazard and unstructured. It is provided when people demand it.	There is a structured program for BIM education and training. This is provided to people who will be working with BIM extensively.	On an organizational level, general information about BIM is communicated to motivate and raise awareness. Extensive training is provided for BIM-oriented individuals and groups.	The BIM educational and training program is tailored to the needs of individuals and target groups. On-the-job training is provided to provide guidance and support in practice.	BIM education and training are constantly updated and improved based on practical experience. Project-specific best and worst practices are valuable input.

Cooperation, openness and transparency	The degree to which people's attitudes are oriented toward collaboration. Openness and transparency to collaboration parties are important factors in this.	The organization is very individualistic. This is also true for BIM implementation.	Collaboration with other parties is limited and reactive, rather than proactive. Openness and transparency are lacking, which impedes collaborative efforts.	Efforts to foster collaboration have been only partially successful. If the organizational culture is more supportive, significant improvements in collaboration with other parties are possible.	Breakthrough in terms of organizational focus on supply chain collaboration. BIM tasks and processes have been successfully aligned with other parties.	External collaboration is a competitive tool that is part of the organization's strategy. Increased mutual trust among partners leads to greater openness and transparency.	A collaborative network within the construction chain goes beyond the interests of individual organizations. The mutual dependence is high, resulting in collaboration taking the lead in competitive position and joint performance.
BIM processes	A collection of BIM-related activities aimed at achieving a specific result. These interdependent activities could, for example, be an application area.	0 – Not present	1 – Initial	2 – Managed	3 – Defined	4 – Quantitatively managed	5 - Optimized
Procedures and work instructions	The level of documentation of organizational and project-related processes. Procedures and work	There are no documented procedures or work instructions for BIM use.	BIM processes have little documentation in the form of procedures or work instructions. As a result, BIM	For important BIM applications, working instructions and/or procedures are established. Despite the presence of some	An organization's use of BIM is documented in working instructions and/or procedures. This includes good practices, with a focus on collaboration with	To ensure the quality of BIM processes, detailed process documentation is provided. This results in predictable	Process documentation is kept current and improved in response to new (BIM) developments. This is done to

	instructions, for example. This has an impact on the consistency and performance of processes.		processes are unpredictable and heavily reliant on individual competencies.	working instructions and procedures, the traditional way of working is still prevalent.	other parties (external processes).	processes and outcomes within acceptable parameters.	ensure that existing documentation remains relevant for BIM usage.
Process change	The extent to which BIM can be used to drive change and improvement in organizational processes.	BIM is viewed as a tool for specific activities, but it does not result in fundamental process optimization.	BIM is, to a limited extent, a motivator for process change and improvement. This is highly dependent on the abilities and motivations of specific individuals or groups.	BIM is a motivator for process improvement, but traditional structures and habits stymie this transition. Project changes are only rarely transferred to other parts of the organization.	BIM is regarded as a powerful tool for process optimization. Changes are communicated to other departments/teams and have an impact on both internal and external processes.	BIM-driven process changes and improvements are actively contributing to process monitoring and adjustment.	BIM helps to optimize processes, at least in part through close collaboration with other parties and disciplines.
ICT (infrastructure)	BIM-related ICT tools, such as hardware and software. This criterion includes meeting rooms and related facilities.	0 – Not present	1 – Initial	2 – Managed	3 – Defined	4 – Quantitatively managed	5 - Optimized
Hardware and network environment	Physical elements and systems required for the use and storage of software and data. The ease with which BIM data can be	Existing hardware is inadequate to support BIM software.	To a limited extent, the hardware supports BIM applications. Processing large amounts of data causes issues. The network	BIM users have access to appropriate hardware. The network infrastructure allows for the exchange of BIM	The organization has some powerful hardware systems. The allocation is based on the dependency of BIM applications.	The hardware is capable of running advanced BIM software applications across the organization. Multiple parties	Current and future BIM needs are actively monitored in order to keep the hardware systems in place up to date.

	accessed and exchanged is determined by the network environment.		environment's infrastructure impedes data exchange with other parties.	data with third parties.		can work in a building model at the same time in the network environment.	
Software	Control and application programs that facilitate BIM applications.	There is no BIM software available.	Although BIM software is available, it only supports BIM to a limited extent.	The available software adequately supports the required BIM use. However, further BIM implementation is hampered.	Collaboration with other parties, including data exchange, is made easier by the available software.	The available software supports all necessary and desired BIM applications. The BIM software serves as a catalyst for further BIM implementation.	Future BIM requirements are regularly mapped in order to keep the software packages in use up to date.
BIM-facilities	The presence, availability, and quality of project and meeting rooms, as well as the associated facilities. This also includes which functions these rooms have in terms of BIM support.	There are no project or meeting rooms available to support BIM use.	There are project rooms and/or meeting rooms available, but they lack facilities. These rooms make little contribution to BIM usage.	The present meeting room(s) are sufficiently equipped to facilitate BIM collaboration. This allows for collaboration with multiple people by using a common screen/monitor.	There are one or more meeting rooms available for teams to use for an extended period of time. This fosters multidisciplinary and integrated collaboration.	One or more meeting rooms are equipped with large projection screens or smartboards to host coordination sessions and support those with BIM.	The demand for BIM-related facilities is constantly being assessed, and necessary changes are identified and implemented.
Data (structure)	Management, structure, (re)use, and exchange of project-related data	0 – Not present	1 – Initial	2 – Managed	3 – Defined	4 – Quantitatively managed	5 - Optimized

Information structure	Use a document management system (DMS) to save data in a structured format and gain access to project data.	There is no document management system in use.	The use of a document management system is unstructured and highly dependent on the competencies of project teams.	The organization's working method includes the use of a document management system. There is no connection between this system and the BIM environment.	The data in the DMS is partially accessible to other project stakeholders. Furthermore, rights to add/change documents can be granted.	The DMS has been fully integrated into the BIM environment. During projects, the DMS serves as a primary source of information and an effective means of communication between parties.	An organization-wide system manages the project-bound data. A single point of contact is designated to ensure the data's quality and consistency.
Object structure/ object decomposition	Building decomposition in which physical and functional parts are defined at various levels of detail. The resulting structure can be used to provide insight into various parts of the building, to create and manage working packages, and to link information to specific elements.	There is no method for building object structure/decomposition.	The object structure is defined at the project level. Within the organization, there is no standardized method for object structure.	Within the organization, a standardized method for object structure is available.	The object structure's organizational method is aligned with projects and shared with other parties.	The method for the object structure is aligned with industry standards. Agreements about the method to be used are reached with partners outside of the project.	Sector-level developments to improve and align the method for object decomposition are closely monitored to keep it up to date.

Object library and object attributes	Standardised objects or concepts from an object library can be used during the construction. The object attributes are a collection of non-graphic information that define, among other things, an object's features and characteristics.	There is no use of an object library.	Various object libraries exist within the organization, but they are not aligned: no standard exists. Attributes are added at random.	An overarching object library exists at the organizational level. Objects are linked to non-geometric basic data.	The object library in use is well-structured, and object naming is consistent. The object library adheres to industry standards.	Available objects and matching attributes from external libraries and open standards are used when creating structures and developing libraries.	Object libraries are constantly updated with new information from projects. To assist other parties and reuse information, object attributes are added.
Data exchange	Data exchange with third parties via or from the structure. As a result, partial designs or data from partners can be used as a basis.	There is no data exchange from the model.	Data exchange through or from the model is limited and unstructured. This exchange is heavily reliant on the project teams' abilities.	Data exchange occurs primarily between teams/departments within the organization. The lack of mutual agreements and/or data standards makes external data exchange more difficult.	Contracts or associated BIM protocols clearly define data exchange with third parties. This is the foundation for successful data exchange and allows other parties to continue with their partial structures.	BIM data is typically exchanged using open standards. This greatly improves the interoperability of structure/BIM data.	BIM data exchange includes indicators that provide insight into the success of BIM applications. This enables continuous monitoring and adjustment, for example, of new application and technology implementation.

A.2. Survey BIM Maturity

1) In which department are you working?
   a) BIM
   b) Planning Engineer
   c) QS
   d) Finance
2) How many years of experience have you been working with BIM in construction project?
   a) Less than 1 year
   b) From 1 to 2 years
   c) From 3 to 4 years
   d) From 5 to 6 years
   e) More than 6 years
3) How many BIM projects have you been involved (including the current one)?
   a) 0
   b) 1
   c) 2
   d) 3
   e) More than 3
4) In which project stage are you usually involved?
   a) Schematic design
   b) Detailed design
   c) Pre-construction
   d) Construction
   e) As built
   f) Other:
5) How often do you work with BIM?
   a) Never
   b) Rarely
   c) Sometimes
   d) Often
   e) Regularly

Strategy

6) What level is a BIM vision and BIM-related goals in your company?
   a) There is no vision or BIM goals present.
   b) A (basic) vision for BIM is defined, but no concrete goals are linked to it.
   c) Generic BIM goals are employed. A BIM-vision is either absent or not in line with the BIM-goals.
   d) The BIM-vision aligns with the organizational vision/strategy and is tailored to close cooperation partners.
   e) BIM-goals are SMART-defined.
   f) A BIM-vision and goals are actively monitored and adjusted as needed.
   g) I'm not sure

7) The level to which management supports BIM implementation and development by providing budgets and explaining the importance of BIM.
   a) There is no management support for BIM.
   b) Inadequate, unstructured BIM support. Budgets are made available on an as-needed basis.

c) Although the importance of BIM is widely acknowledged, budgets are limited.
d) BIM is supported by adequate/appropriate budgets.
e) Appropriate means for developing BIM and implementing new applications are made available.
f) Support for a continuous effort to implement BIM and to ensure future BIM implementation.
g) I'm not sure

8) To what level does the company have a BIM-team and a BIM-expert?
   a) There is no BIM expert, BIM team, or BIM-related department present.
   b) A BIM expert with little time to devote to BIM initiatives. A BIM team or group of core users meets on an irregular basis to discuss BIM implementation.
   c) BIM-expert(s) with adequate time/capacity for BIM implementation.
   d) The BIM-expert collaborates closely with the relevant parts of the organization. A BIM-team or group of core users represents all (relevant) company parts.
   e) Higher management is represented among the BIM expert(s) or BIM-team. There is close collaboration with parts/teams in charge of BIM tasks.
   f) The expert/team's BIM-related discussion is taken into account in order to adjust the BIM strategy based on knowledge, experience, and developments.
   g) I'm not sure.

Organizational structure

9) To what level are BIM-process tasks and responsibilities documented and present within the company?
   a) There is no documentation of tasks and responsibilities for BIM-related processes.
   b) BIM-tasks and responsibilities are incompletely or inadequately documented.
   c) BIM-process tasks and responsibilities are adequately documented, but only to a limited extent integrated into regular job descriptions.
   d) BIM-process tasks and responsibilities are documented at the project level. For this, project teams use (standard) task and role descriptions.
   e) Organizational tasks and responsibilities are adjusted to remain accurate for current BIM use.
   f) Documented BIM-related tasks and responsibilities are evaluated on a regular basis in order to keep them updated in a changing (BIM-) environment.
   g) I'm not sure.

10) To what level are clear agreements regarding BIM made with other parties? (The emphasis is on formal agreements made through contracts, BIM-protocols, or other means.)
   a) BIM is not covered by contracts, protocols, or other written agreements.
   b) Depending on the project or project team, BIM is included in contracts or protocols. Within the organization, there is no standard for this.
   c) The organization established clear guidelines for incorporating BIM into contracts or protocols, but these are rarely followed in practice.
   d) BIM collaboration is explicitly documented in contracts or protocols with third parties. The organization can take the lead in formalizing this process.
   e) BIM-related agreements are specific and measurable, as documented in contracts or protocols: this clarifies which and when information must be delivered.
   f) Changes in BIM use, new insights into BIM, and potential changes in legal conditions are closely monitored in order to adjust contracts and protocols accordingly.
   g) I'm not sure.

People and culture

11) To what level does the company support BIM implementation?
    a) There is skepticism about the implementation of BIM.
    b) On the project level, personal drivers determine whether BIM is used. The organization's culture is not conducive to the transition to BIM.
    c) Despite top-level motivation and early adopters, the majority of the organization lacks enthusiasm for BIM.
    d) There is widespread enthusiasm for BIM within the organization. As a result, there is a greater willingness to change working practices in favor of BIM.
    e) The current organizational culture encourages BIM implementation. Traditional job descriptions and processes are modified to accommodate BIM use.
    f) The organization's strong motivation to improve and implement BIM allows it to quickly adapt to new BIM developments.
    g) I'm not sure.
12) Are there any 'BIM-champions' at the company? (BIM-champions are individuals who take the initiative and are also given the opportunity to coach others on BIM.)
    a) There is no BIM champion present.
    b) A BIM champion is present, but this person lacks the time and capacity to carry out this role effectively.
    c) Despite his ability to advance BIM, the BIM champion has limited time for his role.
    d) The presence of BIM champions, as well as their qualifications to support BIM perspectives from various people, target groups, and departments.
    e) The managing board includes a BIM champion. This person is in close contact with those in charge of operational BIM tasks.
    f) One or more BIM champions from the organization collaborate closely with BIM champions from other organizations.
    g) I'm not sure

13) To what level is BIM-related counseling and guidance provided?
    a) There is no formal education or training in BIM.
    b) BIM education and training is unstructured and not regular. When people demand it, it is provided.
    c) A structured program for BIM education and training is in place. This is provided to people who will be working with BIM extensively.
    d) General information about BIM is communicated at the organizational level in order to motivate and raise awareness. Extensive training is provided for BIM-oriented individuals and groups.
    e) The BIM educational and training program meets the needs of people and target groups. On-the-job training is provided to provide guidance and support in practice.
    f) BIM education and training is kept current and constantly improved based on practical experience. Project-specific best and worst practices are valuable input.
    g) I'm not sure

14) How much emphasis does the company place on collaboration?
    a) The organization is very individualistic. This is also true for BIM implementation.
    b) Collaboration with other parties is haphazard and reactive rather than proactive. Openness and transparency are lacking, stifling collaborative efforts.

c) Structured collaboration efforts are only partially successful. Collaboration with other parties could be significantly improved if the organizational culture was more supportive.
d) A breakthrough in terms of organizational focus on supply chain collaboration. BIM tasks and processes have been successfully aligned with third-party stakeholders.
e) External collaboration is an organizational strategy and a competitive tool. Increased mutual trust among partners leads to greater openness and transparency.
f) A collaborative network within the construction chain extends beyond the interests of individual organizations. The mutual dependence is high, resulting in collaboration taking the lead in competitive position and joint performance.
g) I'm not sure.

BIM processes

15) To what level are organizational and project-related processes documented at the company?
a) No BIM procedures or work instructions are documented.
b) BIM processes are only loosely documented in procedures or work instructions. As a result, BIM processes are unpredictable and heavily reliant on personal competencies.
c) Working instructions and/or procedures are established for critical BIM applications. Although working instructions and procedures are present, the traditional way of working is frequently still used.
d) An organization's BIM use is documented in working instructions and/or procedures. This includes good practices with a focus on collaboration with other parties (external processes).
e) To ensure the quality of BIM processes, detailed process documentation is provided. This results in predictable processes and outcomes within acceptable boundaries.
f) Process documentation is kept up to date and improved in response to new (BIM) developments. This is done to ensure that existing documentation remains relevant for actual BIM use.
g) I'm not sure

16) To what extent is BIM used to optimize internal and external processes?
a) BIM is viewed as a tool for specific activities, but it does not result in fundamental process optimization.
b) BIM is, to a limited extent, a motivator for process change and improvement. This is highly dependent on the abilities and motivations of specific individuals or groups.
c) BIM is a motivator for process improvement, but traditional structures and habits impede this transition. Project changes are only rarely transferred to other parts of the organization.
d) BIM is regarded as a powerful tool for process optimization. Changes are communicated to other departments/teams and have an impact on both internal and external processes.
e) BIM-driven process changes and improvements are actively contributing to process monitoring and adjustment.
f) BIM helps to optimize processes, at least in part through close collaboration with other parties and disciplines.
g) I'm not sure.

ICT (infrastructure)

17) To what extent are hardware systems available for the use of BIM?
a) Existing hardware is insufficient to support BIM software.

b) To a limited extent, the hardware supports BIM applications. Problems arise when processing large amounts of data. The network infrastructure impedes data exchange with other parties.
c) BIM users have access to appropriate hardware. The network infrastructure is sufficient to exchange BIM data with other parties.
d) The organization has some powerful hardware systems. The allocation is based on the dependency of BIM applications.
e) The hardware is capable of executing advanced BIM software applications across the organization. The network environment allows multiple parties to work in a building model at the same time.
f) Current and future BIM needs are actively monitored in order to keep the hardware systems in place up to date.
g) I'm not sure

18) To what extent does the company support BIM software?
a) There is no BIM software available.
b) BIM software is available, but it only supports limited BIM use.
c) The available software adequately supports the required BIM use. However, further BIM implementation is hampered.
d) The available software properly facilitates collaboration with other parties, including data exchange.
e) The available software supports all required and desired BIM applications. The BIM software serves as a catalyst for further BIM implementation.
f) Future BIM needs are regularly mapped in order to keep the software packages in use up to date.
g) I'm not sure.

19) Describe the presence, availability, and quality of BIM facilities.
a) There are no project or meeting rooms available to support BIM use.
b) Project and/or meeting rooms are available but lack amenities. These rooms make little contribution to BIM usage.
c) The meeting room(s) available are adequately equipped to facilitate collaboration with BIM. This allows for collaboration with multiple people by using a shared screen/monitor.
d) There are one or more meeting rooms available for teams to use for an extended period of time. This fosters multidisciplinary and integrated collaboration.
e) One or more meeting rooms are adequately equipped to host coordination sessions and provide BIM support via large projection screens or smartboards.
f) The demand for BIM-related facilities is actively monitored, and any changes that are required are identified and implemented.
g) I'm not sure.

Data (structure)

20) To what extent does the company use a document management system?
a) There is no document management system in use.
b) The use of a document management system is unstructured and highly dependent on project team competencies.
c) The organization's working method includes the use of a document management system. There is no connection between this system and the BIM environment.

d) On a project level, the data in the DMS is partially accessible to other parties. Furthermore, rights to add/change documents can be granted.
e) The DMS is fully integrated within the BIM environment. During projects, the DMS serves as a primary source of information and an effective means of communication between parties.
f) An organization-wide system manages the project-bound data. A single point of contact is designated to ensure the data's quality and consistency.
g) I'm not sure.

21) What is the methodology for an object structure?
a) No method is used for the object structure/decomposition of a building.
b) The used object structure is defined at the project level. Within the organization, there is no uniform method for object structure.
c) The organization has a standardized method for object structure.
d) The organizational method for the object structure is aligned with projects and shared with other parties.
e) As a result, the method for the object structure is aligned with industry standards. Agreements about the method to be used are reached with partners outside of the project.
f) Industry-level developments to improve and align the method for object decomposition are closely monitored to keep it up to date.
g) I'm not sure

22) To what level does the company have an object library?
a) There is no use of an object library.
b) Various object libraries exist within the organization, but they are not aligned. Attributes are added at random.
c) An overarching object library exists at the organizational level. Objects are linked to non-geometric basic data.
d) The object library in use is structured, and object naming is consistent. The object library adheres to industry standards.
e) Available objects and matching attributes from external libraries and open standards are used when creating structures and developing libraries.
f) Object libraries are constantly updated with new data from projects. To assist other parties and reuse information, object attributes are added.
g) I'm not sure.

23) To what level is data through or from the building models exchanged with other parties
a) There is no data exchange from the model.
b) Data exchange through or from the model is limited and unstructured. This exchange is heavily reliant on the project teams' abilities.
c) Data exchange occurs primarily between teams/departments within the organization. The lack of mutual agreements and/or data standards makes external data exchange more difficult.
d) Data exchange with third parties is clearly defined in contracts or BIM protocols. This is the foundation for successful data exchange and provides the option of continuing with the (partial) structure of other parties.
e) The majority of BIM data exchange occurs via open standards. This greatly improves the interoperability of structure/BIM data.

f) BIM data exchange includes indicators that provide insight into the success of BIM applications. This enables continuous monitoring and adjustment, for example, of new application and technology implementation.
g) I'm not sure.

By ticking the box 'I accept', you indicate that you are aware that you are participating in scientific research and that you can terminate your participation at any time by sending an e-mail to n.ngyen.duong.binh@student.tue.nl
Thank you for participating. In case you have any comments, you can leave them here.

Appendix B: Identification of key actors in BIM implementation

B.1. Interview Question

You are invited to the interview to identify the key department that currently involved in the BIM implementation process. Considering the IDD initiatives by Singapore BCA, only advanced BIM implementation would be considered

The information that you provide will be kept strictly confidential and be used solely for academic purposes. Your name will not appear in the study.

Thank you for your kind assistance.

General

- What is your role within your department and within the company
- How would you describe BIM?
- How often are you working with BIM?

Typical Collaboration Scenario

- What is the status of IDD implementation in the company?
- What is the IDD essential use cases currently implemented in your company?
- In the use case before described, what are the department involved in the process?
- Could you briefly describe the collaboration process between these department?
- Are there any project currently implement these use case?

B.2. Interview Summary

The interviewee is a corporate BIM Manager who has over 12 years of experience in BIM projects and a total of 19 years working in the construction industry. He has been involved in the adoption and initiative of BIM technology since 2011 when the Singapore government began implementing it in the construction industry. Throughout his career, he has gained extensive experience in setting up BIM processes and procedures, recruiting BIM manpower, establishing hardware and software requirements for BIM implementation, and conducting research and development of in-house BIM technology.

When discussing the implementation of Integrated Digital Delivery (IDD) within his company, the BIM Manager mentioned that it is challenging to determine the company's IDD implementation status compared to the rest of the industry due to the absence of a framework for evaluation. However, he highlighted that the company recently received the highest award from the Building and Construction Authority (BCA), indicating that the government recognizes the company's IDD capabilities. The management of the company strongly supports digitalization efforts and has made significant investments in manpower and facilities to facilitate this endeavor.

As a main contractor, the company's IDD implementation covers all four phases of IDD, namely digital design, digital fabrication, digital construction, and digital facilities management (FM). The BIM Manager provided various use cases for each phase. For digital design, the company focuses on multi-disciplinary collaboration, ICE sessions/meetings, and digital mock-ups, virtual reality, and digital walkthroughs. In digital fabrication, they utilize QR codes for tracking precast components. In digital construction, the company employs BIM-based shop drawings, 4D sequencing, digital planning progress monitoring, BIM-based cost budgeting, 5D payment claims, and BIM to Field applications such as drone usage and laser scanning. In terms of digital asset delivery, the company primarily produces as-built models.

The BIM Manager mentioned that digital design and digital fabrication implementation within the company is well-organized, benefiting from their extensive experience with BIM and VDC adoption. Most projects have implemented BIM for multi-disciplinary coordination, and coordination meetings, both internal and external, are conducted using construction models as the main source of information, rather than relying solely on 2D drawings. The transition from 2D to 3D coordination and collaboration has been ongoing for a significant period, allowing the technical department, including the BIM department, to fully grasp the usage of BIM technology in their day-to-day work. The production of as-built models and inputting FM parameters for handover to clients is solely handled by the technical department, benefiting from their experience and optimized processes developed through multiple BIM projects.

However, when it comes to collaboration in digital construction processes, particularly involving departments outside the technical department, challenges arise. Solutions such as digital planning progress monitoring, BIM-based cost budgeting, and 5D payment claims are only implemented in selected large-scale or government projects where clients mandate IDD implementation. This client-driven motivation helps reduce resistance from the project teams, making it easier to implement these solutions. However, the results are not consistently stable, and the level of implementation achieved by project teams varies. Currently, the BIM

team is working on upscaling the successful implementation from existing projects to other new projects. The government's aim with IDD is to streamline information flow across various parties in construction projects, as well as between different departments within a construction company. Therefore, these use cases become increasingly relevant and necessary over time to maintain the company's competitiveness.

The collaboration process between departments for specific use cases in digital construction was also discussed. For digital planning progress monitoring, collaboration between the BIM and planning departments is essential. The Planning department works closely with the BIM department to produce weekly progress reports, where the Planning engineer marks up the construction plan to indicate progress, and the BIM team provides the necessary information for calculating work done compared to the overall construction scope.

In the case of cost estimating and budgeting, the QS department collaborates with the BIM team during the tendering process or when determining the budget for awarded projects. The QS team utilizes detailed calculations of material and element quantities provided by the BIM department to accurately estimate project costs, which serves as the baseline for project budgeting.

Project cashflow monitoring and control require close collaboration between the Planning engineer, BIM and QS department. The Planning engineer advises the QS department on the location and area of completed work based on construction progress on a monthly basis. The BIM team generates the quantity of work completed based on the Planning team's mark-up plan. The QS team uses this information to calculate the total quantity completed and generates payment claims for the client. They also handle documentation and payment responses from subcontractors and suppliers while monitoring the project cash flow.

Furthermore, efforts are being made to expand 5D payment claims to involve the finance department for overall company cash flow management. Once the QS department has completed their tasks for payment claim, they transfer all relevant documentation and calculations to the Finance department. The Finance team uses this information to monitor and control the company's overall cash flow. They receive payments from clients and process payments to subcontractors and suppliers based on the project-specific details provided by the QS department. Currently, the exchange process between the QS and finance departments is mostly document-based and involves a significant amount of manual input. The objective is to streamline this process by digitalizing the data exchange process between both departments.

Appendix C: Barriers to BIM and Interventions

C.1. Interview Questions

You are invited to the interview to explore what is the barriers to BIM implementation of the company. The objective of this interview is to identify barriers experience by your department in BIM implemented project and the potential solution to overcome them.

The information that you provide will be kept strictly confidential and be used solely for academic purposes. Your name and your project's name will not appear in the study.

Thank you for your kind assistance.

General

- What is your role within your department and within the company
- How would you describe BIM?
- How often are you working with BIM?
- In your opinions, what is the impact that BIM brought to the project?

Barriers experienced

- What was the most recent BIM project in which you were involved?
- Are there any other department involved in BIM in your project besides yours?
- What is the involvement level of the previously mentioned departments?
- What barriers have you encountered in implementing BIM in your project?
- How do these barriers affect the project?
- Aside from these barriers in this project, have you encountered any other BIM barriers in previous projects?
- What is the most difficult barrier for you? Why?

Solution to overcome the barriers

- How, in your opinion, could the aforementioned barriers be solved or reduced?
- What is the desired outcome you believe the solution can achieve?
- What are your views on the company's current BIM implementation?
- Which organizational level has the most influence over the implementation of this solution?

Verification of game model

- Refer to the sub-task breakdown for major task, to what extent this list correctly reflects the procedure for each task?
- What is the manpower requirement for each sub-task related to your department?
- What is the software requirement for each sub-task related to your department

SUB-TASK BREAKDOWN FOR MARJOR TASK

	Scenario 1: Project schedule monitoring and control	**Scenario 2: Cost estimating and budgeting**	**Scenario 3: Project cashflow monitoring and control**	**Scenario 4: Company cashflow monitoring and control**
Collaboration Team 1: Traditional	1. Setting up monitoring system 2. Gathering construction information 3. Update construction schedule 4. Generate mark up plan	1. Studying construction drawing 2. Quantity takeoff 3. Tabulation	1. Setting up monitoring system 2. Gathering construction information 3. Update construction schedule 4. Generate mark up plan 5. Quantity take-off 6. Tabulation for payment claim 7. Gathering document from subcon 8. Tabulation for payment response	1. Setting up monitoring system 2. Gathering construction information 3. Update construction schedule 4. Quantity take-off 5. Tabulation for payment claim 6. Gathering document from subcon 7. Tabulation for payment response 8. Input to financial system 9. Verification and monitoring 10. Cashflow summary
Collaboration Team 2: Traditional + BIM	1. Setting up monitoring system 2. Setting up model 3. Gathering construction information 4. Update construction schedule 5. Generate mark up plan	1. Constructing model 2. Quantity takeoff 3. Tabulation	1. Setting up monitoring system 2. Setting up model 3. Gathering construction information 4. Update construction schedule 5. Generate mark up plan 6. Quantity take-off 7. Tabulation for payment claim 8. Gathering document from subcon 9. Tabulation for payment response	1. Setting up monitoring system 2. Setting up model 3. Gathering construction information 4. Update construction model 5. Quantity take-off 6. Tabulation for payment claim 7. Gathering document from subcon 8. Tabulation for payment response 9. Input to financial system 10. Verification and monitoring 11. Cashflow summary
Collaboration Team 3:	1. Setting up monitoring system 2. Setting up model	1. Constructing model 2. Quantity takeoff 3. Tabulation	1. Setting up monitoring system 2. Setting up model	1. Setting up monitoring system 2. Setting up model

Traditional + BSP	3. Gathering construction information 4. Update construction schedule 5. Generate mark up plan		3. Gathering construction information 4. Update construction schedule 5. Generate mark up plan 6. Quantity take-off 7. Tabulation for payment claim 8. Gathering document from subcon 9. Tabulation for payment response	3. Gathering construction information 4. Update construction model 5. Quantity take-off 6. Tabulation for payment claim 7. Gathering document from subcon 8. Tabulation for payment response 9. Input to financial system 10. Verification and monitoring 11. Cashflow summary
Collaboration Team 4: Traditional + BIM + BSP	1. Setting up monitoring system 2. Setting up model 3. Gathering construction information 4. Update construction schedule 5. Generate mark up plan	1. Constructing model 2. Quantity takeoff 3. Tabulation	1. Setting up monitoring system 2. Setting up model 3. Gathering construction information 4. Update construction schedule 5. Generate mark up plan 6. Quantity take-off 7. Tabulation for payment claim 8. Gathering document from subcon 9. Tabulation for payment response	1. Setting up monitoring system 2. Setting up model 3. Gathering construction information 4. Update construction model 5. Quantity take-off 6. Tabulation for payment claim 7. Gathering document from subcon 8. Tabulation for payment response 9. Input to financial system 10. Verification and monitoring 11. Cashflow summary

C.2. Interview Summary

C.2.1. BIM Department

The interview consisted of four persons from the BIM department, including the corporate BIM manager and three senior BIM specialists who are actively involved in ongoing projects implementing various IDD (Integrated Digital Delivery) solutions. All interviewees possess extensive experience in implementing BIM both from a project and organizational perspective, as well as collaborating with other departments within the company for BIM implementation.

During the interview, the participants agreed that while BIM has numerous benefits when implemented in projects, there are still barriers that need to be overcome, particularly in collaboration with outside departments within project teams. The interviewees were briefed on the objectives of the interview, which focused on identifying departmental barriers and proposing solutions that were agreed upon by all interviewees.

The following barriers were identified and agreed upon by all interviewees:

1. Greater hardware and software specifications requirements due to larger BIM models or equipment needed to view digital models.

    1.1. The size and complexity of BIM models require better laptops and computers, leading to increased project budgets. However, budget constraints may hinder BIM implementation if project leaders are not fully supportive.

    1.2. Other departments also need to transition from low-spec laptops to more expensive BIM laptops to reduce dependency on the BIM department.

    1.3. Slow internet speed in project site offices affects the efficiency of opening and operating large BIM models compared to the head office.

2. Resistance to change from traditional workflows to BIM workflows.

    2.1. Persuading departments to change their well-established and optimized workflows is challenging. Demonstrating the benefits of BIM is crucial, but the return on investment may remain unclear.

    2.2. Resistance from key individuals, such as project managers, can easily transfer to others, impacting the extent of BIM adoption within the project organization.

2.3. Finding a balance between the pace of change and change capabilities is necessary, as productivity may initially decrease during the transition period.

3. Training and upskilling of BIM and department staff, and transferring knowledge and lessons learned to the organization.

3.1. BIM personnel often lack knowledge and experience in construction methods and workflows of other departments, leading to misalignment and reduced trust in BIM outputs.

3.2. Upscaling lessons learned from individual projects to the organizational level is challenging due to project variations and differing project teams and leaders.

4. Inadequate software in the market suited to the desired departmental workflow and output format.

4.1. Available software may not be well-established or customized to local work practices, requiring significant time and cost for integration into workflows.

4.2. User-friendly and easy-to-use software is essential to gain trust from other department staff, as they need assurance of accurate outputs and error-checking mechanisms.

Based on these barriers, the interviewees proposed interventions to overcome them:

1. Allocate additional budgets for hardware and software dedicated to BIM implementation, with the understanding that these investments will yield increased productivity and enhance company competitiveness in the long run. Software costs can be controlled through network licenses for infrequently used software, and web applications should be considered to provide flexibility in accessing and using software without fixed installation points.

2. Establish a group of specialists within the department focused on liaising and collaborating with other departments.

2.1. These specialists should possess expertise in both BIM and technical aspects to bridge operational and procedural gaps between departments, fostering transparent and open communication.

2.2. By working closely with other department staff and proactively addressing their concerns, trust can be built, leading to more comprehensive collaboration.

2.3. Over time, increased trust will help reduce resistance to change and promote greater adoption of BIM.

3. Leverage the same group of specialists as subject matter experts to transfer knowledge and experience to other BIM staff. These experts, having knowledge beyond the scope of BIM, can help train and elevate the knowledge level of their colleagues. Implementing a knowledge management system is crucial for structured management of training programs, recruitment, and training for new staff.

4. Develop in-house software tailored to the department's workflow, which may initially require higher costs but can be offset by license-free usage and adaptability to the company's procedures. This software can be further developed into web applications, centralizing information for easy access by other departments and providing data extraction capabilities as needed.

All interviewees agreed that both management and operational levels have influence over implementing these solutions. While management provides support in terms of direction, strategic planning, and financial incentives, the operational level is where real change occurs and enhances productivity and management efficiency.

At the end of the session, the interviewees were asked to verify the game model, which initially raised some queries regarding the formulation of actors being each department in the collaboration process. The interviewer explained that the BIM department plays a supporting role, and each department alone cannot complete the task, justifying the chosen game model. The interviewees agreed with this reasoning and proceeded to review the game model. No objections were raised concerning the task breakdown list.

The manpower and software requirements from the BIM department for each collaboration team were tabulated, and the interviewees acknowledged the accuracy of the information provided. During the interview, it was noted that the expectations of BIM specialists in each collaboration team were higher due to their expertise and experience with BIM. They were expected to serve as a bridge between the BIM department and other departments, not only fulfilling their BIM tasks but also assisting other departments to expedite the process.

Traditional+BIM	**Manpower**	**Software**	**Traditional+BSP**	**Manpower**	**Software**	**Traditional+BIM+BSP**	**Manpower**	**Software**
Project schedule monitoring and control								
Setting up monitoring system	2 BIM	revit	Setting up monitoring system	2 BSP	revit	Setting up monitoring system	2 BIM, 1 BSP	revit
Setting up model	2 BIM	revit	Setting up model	2 BSP	revit	Setting up model	2 BIM, 1 BSP	revit
Gathering construction information			Gathering construction information			Gathering construction information		

Update construction model	2 BIM	revit	Update construction model	2 BSP	revit	Update construction model	2 BIM, 1 BSP	revit
Generate mark up plan	2 BIM	revit, 5D	Generate mark up plan	2 BSP	revit, 5D	Generate mark up plan	2 BIM, 1 BSP	revit, 5D
Cost estimating and budgeting								
Constructing model	3 BIM	revit	Constructing model	3 BSP	revit	Constructing model	3 BIM, 1 BSP	revit
Quantity takeoff	3 BIM	revit, 5D	Quantity takeoff	3 BSP	revit, 5D	Quantity takeoff	3 BIM, 1 BSP	revit, 5D
Tabulation	1 BIM	revit, 5D	Tabulation	1 BSP	revit, 5D	Tabulation	1 BSP	revit, 5D
Project cashflow monitoring and control								
Setting up monitoring system			Setting up monitoring system			Setting up monitoring system		
Setting up model	3 BIM	revit, 5D	Setting up model	3 BSP	revit, 5D	Setting up model	3 BIM, 1 BSP	revit, 5D
Gathering construction information			Gathering construction information			Gathering construction information	1 BSP	revit
Update construction model	3 BIM	revit, 5D	Update construction model	3 BSP	revit, 5D	Update construction model	3 BIM, 1 BSP	revit, 5D
Generate mark up plan	3 BIM	revit, 5D	Generate mark up plan	3 BSP	revit, 5D	Generate mark up plan	3 BIM, 1 BSP	revit, 5D
Quantity take-off	3 BIM	revit, 5D	Quantity take-off	3 BSP	revit, 5D	Quantity take-off	3 BIM, 1 BSP	revit, 5D
Tabulation for payment claim			Tabulation for payment claim	1 BSP	revit, 5D	Tabulation for payment claim	1 BSP	revit, 5D
Gathering document from subcon			Gathering document from subcon			Gathering document from subcon		
Tabulation for payment response			Tabulation for payment response			Tabulation for payment response		
Company cashflow monitoring and control								
Setting up monitoring system			Setting up monitoring system			Setting up monitoring system		
Setting up model	3 BIM	revit, 5D	Setting up model	3 BSP	revit, 5D	Setting up model	3 BIM, 1 BSP	revit, 5D
Gathering construction information			Gathering construction information			Gathering construction information	1 BSP	revit

Update construction model	3 BIM	revit, 5D	Update construction model	3 BSP	revit, 5D	Update construction model	3 BIM, 1 BSP	revit, 5D
Quantity take-off	3 BIM	revit, 5D	Quantity take-off	3 BSP	revit, 5D	Quantity take-off	3 BIM, 1 BSP	revit, 5D
Tabulation for payment claim			Tabulation for payment claim	1 BSP	revit, 5D	Tabulation for payment claim	1 BSP	revit, 5D
Gathering document from subcon			Gathering document from subcon			Gathering document from subcon		
Tabulation for payment response			Tabulation for payment response			Tabulation for payment response		
Input to financial system			Input to financial system			Input to financial system		
Verification and monitoring			Verification and monitoring			Verification and monitoring		
Cashflow summary			Cashflow summary			Cashflow summary		

C.2.2. Planning Department

The interview consisted of a planning manager and a planning engineer who are currently involved in a large-scale and complex IDD project. With four years of experience in implementing BIM for progress monitoring and project cashflow, they have gained significant insights into the process and workflow. The interviewees understood the objectives of the interview, which aimed to identify departmental barriers and propose agreed-upon solutions.

According to the interviewees, their definition of BIM aligns with the one used in the study. While they acknowledged the benefits of BIM in reducing workload and improving project outcomes, they believed that there is still room for improvement in achieving higher levels of collaboration between departments within projects and across the organization.

The barriers identified by the interviewees are as follows:

1. Difficulty in changing the traditional workflow to a BIM workflow.

    1.1. Well-established procedures make it easier to control results and detect errors, posing challenges in transitioning to new workflows.

    1.2. The transition period from traditional to BIM workflows may lead to stress and decreased productivity as both processes run concurrently.

    1.3. Alignment of objectives and collaboration between departments needs to be addressed to increase productivity without disrupting daily work.

2. Lack of construction method knowledge and technical expertise among BIM personnel.

    2.1. BIM personnel may not be well-trained in capturing and updating construction progress or setting up monitoring systems.

    2.2. Communication and understanding between departments may be hindered due to limited knowledge of construction processes and methods.

3. Greater hardware and software specifications requirements due to larger BIM models.

    3.1. Large BIM models require better hardware to run effectively, increasing project budgets.

    3.2. Budget constraints and lack of support from project leaders can hinder the implementation of BIM hardware and software.

4. Limitations in existing software available in the market.

    4.1. Software may lack flexibility to adapt to company procedures and output requirements, sometimes leading to faster and easier completion of tasks using traditional methods.

    4.2. Maintaining multiple systems concurrently can increase workload and provide marginal improvements in productivity.

5. Time pressure and resistance to change.

    5.1. Initial productivity drops during the implementation period may discourage staff and lead to a loss of trust in the system.

    5.2. The instability of initial implementation results may create skepticism, pushing people back towards traditional methods.

    5.3. Training efforts require additional time and effort, adding stress to staff members.

    5.4. Designing a comprehensive monitoring system can be time-consuming, requiring input from planning and field staff, who may be hesitant to participate.

6. Challenges in engaging field staff in using BIM for updating construction progress.

    6.1. Field staff may be resistant to using BIM applications due to increased workload and lack of training in operating digital systems.

To address these barriers, the interviewees proposed the following interventions:

1. Establish a group of facilitators from the BIM team who understand planning requirements and procedures. These facilitators would advise the planning team on applying BIM solutions to their workflows, emphasizing time savings and providing collaboration support during the transition period.

2. Organize training programs or knowledge-sharing sessions between the planning and BIM departments to bridge knowledge gaps. Planning staff can share construction method expertise, scheduling, and monitoring procedures, while BIM staff can teach planning department members BIM software applications and processes.

3. Allocate additional budgets for BIM hardware and software. Better hardware and software can increase interest and positive perceptions of BIM implementation, enhancing overall productivity.

4. Develop in-house software that aligns with the company's workflow and procedures. This offers greater flexibility, reduces the need for multiple systems, and lowers the learning curve for staff.

5. Mitigate time pressure and resistance to change through close collaboration between the BIM and planning departments. Facilitators can align workflows and procedures and provide guidance on the best roadmap for BIM implementation.

6. Address the challenge of engaging field staff by considering mobile applications as a solution. Simplified interfaces and proper training can encourage field staff to participate in updating construction progress using BIM.

Regarding the influence of organizational levels on BIM implementation, the interviewees agreed that management level and the BIM department play crucial roles. While the planning department can contribute to the overall implementation, they lack the necessary BIM technology knowledge to fully leverage its potential.

During the verification of the game model, the interviewees understood the reasons and logic behind the model setup. They confirmed that two personnel from the planning department are typically involved in large to medium-scale projects. They also mentioned using Excel for all four collaboration scenarios, while other dedicated project scheduling tools are used for different tasks.

C.2.3 QS Department

The interview consisted of a contract manager and a senior quantity surveyor (QS) who are actively involved in a large-scale and complex IDD (Integrated Digital Delivery) project. With their extensive experience in implementing BIM for progress monitoring, project cashflow, and budgeting, the interviewees provided valuable insights into the process and workflow. They were well-informed about the objectives of the interview, which aimed to identify departmental barriers and propose agreed-upon solutions.

The interviewees shared a common understanding of BIM, recognizing its benefits in reducing workload and improving project outcomes. However, they believed that further improvements could be made to enhance collaboration between departments within projects and across the organization.

The barriers identified by the interviewees are as follows:

1. Difficulty in changing the traditional workflow to a BIM workflow.

    1.1. Establishing objective alignment and collaboration between departments presents challenges in adjusting procedures to increase productivity without disrupting daily work.

    1.2. The transition period from traditional to BIM workflows may lead to stress, decreased productivity, and a loss of control over results.

    1.3. Well-established procedures in place for a long period of time make it easier to control results and detect errors.

2. Time pressure and resistance to change.

    2.1. Initial productivity drops during the implementation period may discourage staff and create frustration.

    2.2. The instability of initial implementation results may lead to a loss of trust in the system, driving a return to traditional methods.

    2.3. Additional time and effort are required for training, creating stress for staff members.

3. Lack of technical experience and quantity take-off techniques among BIM personnel.

    3.1. BIM personnel may lack training on QS functions, such as quantity calculations and cost control, leading to challenges in advising on correct calculation methods.

    3.2. Limited understanding of construction processes and methods can hinder communication and collaboration between departments.

4. Limitations in the current software available in the market.

    4.1. Existing software may not be well-established or customized to local work practices, requiring substantial time and cost investments to integrate them into workflows.

    4.2. Lack of flexibility in software can hinder its adaptation to company procedures and output requirements for other departments.

5. Greater hardware and software specifications requirements due to larger BIM models.

    5.1. Large BIM models require better hardware, increasing project budgets.

    5.2. Budget constraints and lack of support from project leaders can hinder the implementation of BIM hardware and software.

To address these barriers, the interviewees proposed the following interventions:

1. Establish a group of facilitators from the BIM team who understand QS requirements and methods. These facilitators would advise QS staff on applying BIM solutions to their workflows, saving time and improving efficiency. The facilitators can also adjust modeling methods to align with quantity take-off techniques. Collaboration and trust-building are crucial to ensure a smooth transition without disrupting daily work.

2. Foster close collaboration between the BIM and QS teams to reduce time pressure during the transition period. By working together and proactively solving problems, stress levels can be reduced. BIM team members can advise QS staff on using BIM for faster quantity take-offs, while QS staff can provide technical expertise and assist in optimizing BIM processes for QS tasks. Facilitators play a vital role in aligning workflows and procedures, providing guidance for the best roadmap to implement BIM.

3. Organize training programs or knowledge-sharing sessions between the QS and BIM departments to bridge knowledge gaps. These sessions should focus on sharing quantity take-off procedures, progress claim methods, BIM software applications, and BIM processes. The goal is to foster comprehensive collaboration between the departments.

4. Develop in-house software that can be tailored to the department's workflow and procedures. This approach offers greater flexibility, reduces the need for multiple systems, and eases the learning curve for QS staff, reducing stress during the transition.

5. Allocate additional budget for BIM hardware and software. Improved hardware and software can empower QS staff to operate and extract data independently, enhancing accuracy and reducing dependence on the BIM team.

Regarding the influence of organizational levels on BIM implementation, the interviewees agreed that management level and the BIM department play crucial roles. While the QS department can contribute to the overall implementation, they acknowledged the need for BIM technology knowledge to fully leverage its potential.

During the verification of the game model, the interviewees understood the reasons and logic behind the model setup. They suggested adding two additional activities related to payment response for subcontractors to cover the complete cashflow of the project. Regarding manpower requirements, they stated that at least three QS personnel are typically involved in cost budgeting tasks for each project. For project and company cashflow monitoring, the number of QS involved varies based on the project timeline, with the peak periods requiring the involvement of the entire project QS team. On average, they estimated three QS personnel to be involved throughout the project lifecycle. The interviewees mentioned that they primarily use Excel for their tasks.

C.2.4. Finance Department

The interview consisted of a finance manager and a finance executive who were actively involved in the implementation of IDD (Integrated Digital Delivery) for company workflow monitoring tasks. Despite their relatively limited experience of around one year with this new process, they expressed optimism about its potential efficiency and have already witnessed some of the benefits it brings.

Both interviewees shared a common understanding of BIM and recognized its advantages in reducing workload and improving project outcomes. However, they believed that further improvements could enhance collaboration between departments within projects and across the organization.

The barriers identified by the interviewees are as follows:

1. Software not well-suited to the requirements:

    1.1. Slow technology development, lack of software interoperability, and non-user-friendly formats were significant concerns.

    1.2. Market-available software was not well-established or customized to local work practices, resulting in substantial time and cost spent on exploring and integrating such processes into the workflow.

2. Lack of BIM knowledge in the finance team and technical knowledge in the BIM team:

    2.1. Limited lessons and experience were available on developing a practical and efficient system.

    2.2. Differences in education backgrounds and technical expertise between department personnel made communication and concept understanding difficult.

    2.3. Time and cost were required for human resource training.

3. Incomplete implementation:

    3.1. Only a part of the job scope was digitalized, requiring the maintenance of multiple systems concurrently and creating risks of errors and lack of synchronization between systems.

4. Risk of security in sensitive data handling:

4.1. Concerns over who can access and modify data, particularly considering the sensitive nature of finance data that can affect the company's commercial interests.

4.2. Risks of data leakage to outsiders, potentially reducing the company's competitiveness.

To address these barriers, the interviewees proposed the following interventions:

1. Develop in-house software that can be tailored to the finance department's workflow and procedures, reducing the need to maintain multiple systems. Familiarity with the new software and its alignment with established procedures would lower the learning curve and facilitate a smoother transition for staff.

2. Establish a group of facilitators from the BIM team who understand the finance department's requirements and procedures. These facilitators would advise finance staff on applying BIM solutions to their workflow, while also transferring knowledge to the in-house developer team to better tailor the software to end-users' needs. The facilitators would bridge the gap in background and knowledge between the departments, particularly considering that most BIM staff have construction backgrounds rather than financial expertise.

3. Strive for a comprehensive implementation where all finance operation functions are integrated into a single platform, along with other relevant parts of the department within the organization. This integrated platform would provide a single version of true financial performance reporting, enhancing efficiency, collaboration, and task effectiveness while reducing rework and opportunities for error and waste. It would ensure that all departments are on the same page, rather than isolated in their own systems.

4. Implement proper measures to reduce the risk of data breaches. This includes defining the roles and responsibilities of staff involved in the system and ensuring that adequate safeguards are in place, particularly as the system is scaled up to the organizational level.

During the verification of the game model, the interviewees understood the reasons and logic behind the model setup. The detailed task list for the finance team had not been established prior to the interview, so the activities for finance team involvement in company cashflow monitoring were added based on their input. For manpower requirements, since this was the first project utilizing the new technology, only two personnel from the finance department were involved. The interviewees mentioned using both Excel and their dedicated finance software for their tasks.

Appendix D: Intervention Effectiveness in Overcoming BIM Barriers

Measure 1: Formulation of specialist group for collaboration and integration

In the interview, first barrier was indicated different department have their own well-established function and protocols; thus, objective alignment and collaboration is difficult. The implementation is usually not comprehensive, creating the situation where multiple systems are required to operate concurrently. This situation ultimately led to resistance to change in transitioning period due to increasing stress level and time pressure

Therefore, the following measure is proposed:

Formulation of specialist group for collaboration and integration: This group would serve as a facilitator, bridging the gap between different procedures and background knowledge. They would also act as advisors and trainers, improving the technical understanding of BIM staff and providing guidance on integration initiatives for other departments.

In order to understand the effect of this measure, this section presents 4 scenarios. For each scenario, please input the engineering time required to completed specific task in 4 cases: traditional process, with the assistance of 3 BIM Modeler, with the assistance of 3 BIM Specialist (BSP) personnel, and with assistance of 3 BIM personnel and 1 BSP personnel

Traditional	**Time**	**Traditional+ 3 BIM**	**Time**	**Traditional+ 3 BSP**	**Time**	**Traditional+3 BIM+1 BSP**	**Time**
Project schedule monitoring and control							
Setting up monitoring system		Setting up monitoring system		Setting up monitoring system		Setting up monitoring system	
Gathering construction information		Setting up model		Setting up model		Setting up model	
Update construction schedule		Gathering construction information		Gathering construction information		Gathering construction information	
Generate mark up plan		Update construction model		Update construction model		Update construction model	
		Generate mark up plan		Generate mark up plan		Generate mark up plan	
Cost estimating and budgeting							
Studying construction drawing		Constructing model		Constructing model		Constructing model	
Quantity takeoff		Quantity takeoff		Quantity takeoff		Quantity takeoff	
Tabulation		Tabulation		Tabulation		Tabulation	
Project cashflow monitoring and control							

Setting up monitoring system		Setting up monitoring system		Setting up monitoring system		Setting up monitoring system	
Gathering construction information		Setting up model		Setting up model		Setting up model	
Update construction schedule		Gathering construction information		Gathering construction information		Gathering construction information	
Generate mark up plan		Update construction model		Update construction model		Update construction model	
Quantity take-off		Generate mark up plan		Generate mark up plan		Generate mark up plan	
Tabulation for payment claim		Quantity take-off		Quantity take-off		Quantity take-off	
Gathering document from subcon		Tabulation for payment claim		Tabulation for payment claim		Tabulation for payment claim	
Tabulation for payment response		Gathering document from subcon		Gathering document from subcon		Gathering document from subcon	
		Tabulation for payment response		Tabulation for payment response		Tabulation for payment response	
Company cashflow monitoring and control							
Setting up monitoring system		Setting up monitoring system		Setting up monitoring system		Setting up monitoring system	
Gathering construction information		Setting up model		Setting up model		Setting up model	
Update construction schedule		Gathering construction information		Gathering construction information		Gathering construction information	
Quantity take-off		Update construction model		Update construction model		Update construction model	
Tabulation for payment claim		Quantity take-off		Quantity take-off		Quantity take-off	
Gathering document from subcon		Tabulation for payment claim		Tabulation for payment claim		Tabulation for payment claim	
Tabulation for payment response		Gathering document from subcon		Gathering document from subcon		Gathering document from subcon	
Input to financial system		Tabulation for payment response		Tabulation for payment response		Tabulation for payment response	
Verification and monitoring		Input to financial system		Input to financial system		Input to financial system	
Cashflow summary		Verification and monitoring		Verification and monitoring		Verification and monitoring	
		Cashflow summary		Cashflow summary		Cashflow summary	

Measure 2: Additional training program and knowledge sharing session

In the interview, second barrier was indicated that digital tools are relatively new to all participating parties and there was a steep learning curve at the start, leading to a drop in productivity at the start of implementation. Difference in background and knowledge create the gap in communication and collaboration and reduce trust level. Mindset change become significant obstacle

Therefore, the following measure is proposed:

Additional training program and knowledge sharing session: establishing a training program and knowledge-sharing sessions among departments. This initiative aims to foster a common understanding and enhance the overall knowledge level of the involved departments

In order to understand the effect of this measure, this section presents 4 scenarios. For each scenario, please input the engineering time required to completed specific task in 4 cases: traditional process, with the assistance of 3 BIM Modeler, with the assistance of 3 BIM Specialist (BSP) personnel, and with assistance of 3 BIM personnel and 1 BSP personnel

Traditional	**Time**	**Traditional+ 3 BIM**	**Time**	**Traditional+ 3 BSP**	**Time**	**Traditional+3 BIM+1 BSP**	**Time**
Project schedule monitoring and control							
Setting up monitoring system		Setting up monitoring system		Setting up monitoring system		Setting up monitoring system	
Gathering construction information		Setting up model		Setting up model		Setting up model	
Update construction schedule		Gathering construction information		Gathering construction information		Gathering construction information	
Generate mark up plan		Update construction model		Update construction model		Update construction model	
		Generate mark up plan		Generate mark up plan		Generate mark up plan	
Cost estimating and budgeting							
Studying construction drawing		Constructing model		Constructing model		Constructing model	
Quantity takeoff		Quantity takeoff		Quantity takeoff		Quantity takeoff	
Tabulation		Tabulation		Tabulation		Tabulation	
Project cashflow monitoring and control							
Setting up monitoring system		Setting up monitoring system		Setting up monitoring system		Setting up monitoring system	
Gathering construction information		Setting up model		Setting up model		Setting up model	
Update construction schedule		Gathering construction information		Gathering construction information		Gathering construction information	

Generate mark up plan		Update construction model		Update construction model		Update construction model	
Quantity take-off		Generate mark up plan		Generate mark up plan		Generate mark up plan	
Tabulation for payment claim		Quantity take-off		Quantity take-off		Quantity take-off	
Gathering document from subcon		Tabulation for payment claim		Tabulation for payment claim		Tabulation for payment claim	
Tabulation for payment response		Gathering document from subcon		Gathering document from subcon		Gathering document from subcon	
		Tabulation for payment response		Tabulation for payment response		Tabulation for payment response	
Company cashflow monitoring and control							
Setting up monitoring system		Setting up monitoring system		Setting up monitoring system		Setting up monitoring system	
Gathering construction information		Setting up model		Setting up model		Setting up model	
Update construction schedule		Gathering construction information		Gathering construction information		Gathering construction information	
Quantity take-off		Update construction model		Update construction model		Update construction model	
Tabulation for payment claim		Quantity take-off		Quantity take-off		Quantity take-off	
Gathering document from subcon		Tabulation for payment claim		Tabulation for payment claim		Tabulation for payment claim	
Tabulation for payment response		Gathering document from subcon		Gathering document from subcon		Gathering document from subcon	
Input to financial system		Tabulation for payment response		Tabulation for payment response		Tabulation for payment response	
Verification and monitoring		Input to financial system		Input to financial system		Input to financial system	
Cashflow summary		Verification and monitoring		Verification and monitoring		Verification and monitoring	
		Cashflow summary		Cashflow summary		Cashflow summary	

Measure 3: In-house software development

In the interview, third barrier was indicated that digital tools and technologies were not well established and/or not customized to local work practices; therefore, substantial amount of time and cost were spent in the exploration and trials for the integration of such processes into the workflow.

Therefore, the following measure is proposed:

In-house software development: in-house software that can be customized to fit the specific workflows and procedures, developed internally by the company

In order to understand the effect of this measure, this section presents 4 scenarios. For each scenario, please input the engineering time required to completed specific task in 4 cases: traditional process, with the assistance of 3 BIM Modeler, with the assistance of 3 BIM Specialist (BSP) personnel, and with assistance of 3 BIM personnel and 1 BSP personnel

Traditional	**Time**	**Traditional+ 3 BIM**	**Time**	**Traditional+ 3 BSP**	**Time**	**Traditional+3 BIM+1 BSP**	**Time**
Project schedule monitoring and control							
Setting up monitoring system		Setting up monitoring system		Setting up monitoring system		Setting up monitoring system	
Gathering construction information		Setting up model		Setting up model		Setting up model	
Update construction schedule		Gathering construction information		Gathering construction information		Gathering construction information	
Generate mark up plan		Update construction model		Update construction model		Update construction model	
		Generate mark up plan		Generate mark up plan		Generate mark up plan	
Cost estimating and budgeting							
Studying construction drawing		Constructing model		Constructing model		Constructing model	
Quantity takeoff		Quantity takeoff		Quantity takeoff		Quantity takeoff	
Tabulation		Tabulation		Tabulation		Tabulation	
Project cashflow monitoring and control							
Setting up monitoring system		Setting up monitoring system		Setting up monitoring system		Setting up monitoring system	
Gathering construction information		Setting up model		Setting up model		Setting up model	
Update construction schedule		Gathering construction information		Gathering construction information		Gathering construction information	

Generate mark up plan		Update construction model		Update construction model		Update construction model	
Quantity take-off		Generate mark up plan		Generate mark up plan		Generate mark up plan	
Tabulation for payment claim		Quantity take-off		Quantity take-off		Quantity take-off	
Gathering document from subcon		Tabulation for payment claim		Tabulation for payment claim		Tabulation for payment claim	
Tabulation for payment response		Gathering document from subcon		Gathering document from subcon		Gathering document from subcon	
		Tabulation for payment response		Tabulation for payment response		Tabulation for payment response	
Company cashflow monitoring and control							
Setting up monitoring system		Setting up monitoring system		Setting up monitoring system		Setting up monitoring system	
Gathering construction information		Setting up model		Setting up model		Setting up model	
Update construction schedule		Gathering construction information		Gathering construction information		Gathering construction information	
Quantity take-off		Update construction model		Update construction model		Update construction model	
Tabulation for payment claim		Quantity take-off		Quantity take-off		Quantity take-off	
Gathering document from subcon		Tabulation for payment claim		Tabulation for payment claim		Tabulation for payment claim	
Tabulation for payment response		Gathering document from subcon		Gathering document from subcon		Gathering document from subcon	
Input to financial system		Tabulation for payment response		Tabulation for payment response		Tabulation for payment response	
Verification and monitoring		Input to financial system		Input to financial system		Input to financial system	
Cashflow summary		Verification and monitoring		Verification and monitoring		Verification and monitoring	
		Cashflow summary		Cashflow summary		Cashflow summary	

Measure 4: Additional budget for BIM facilities

In the interview, fourth barrier was indicated that greater specifications requirement of hardware and software or equipment needed to view digital models, due to larger sizes of BIM models

Therefore, the following measure is proposed:

Additional budget for BIM facilities: more budget allowance for procurement of better computer, laptop, equipment and software

In order to understand the effect of this measure, this section presents 4 scenarios. For each scenario, please input the engineering time required to completed specific task in 4 cases: traditional process, with the assistance of 3 BIM Modeler, with the assistance of 3 BIM Specialist (BSP) personnel, and with assistance of 3 BIM personnel and 1 BSP personnel

Traditional	**Time**	**Traditional+ 3 BIM**	**Time**	**Traditional+ 3 BSP**	**Time**	**Traditional+3 BIM+1 BSP**	**Time**
Project schedule monitoring and control							
Setting up monitoring system		Setting up monitoring system		Setting up monitoring system		Setting up monitoring system	
Gathering construction information		Setting up model		Setting up model		Setting up model	
Update construction schedule		Gathering construction information		Gathering construction information		Gathering construction information	
Generate mark up plan		Update construction model		Update construction model		Update construction model	
		Generate mark up plan		Generate mark up plan		Generate mark up plan	
Cost estimating and budgeting							
Studying construction drawing		Constructing model		Constructing model		Constructing model	
Quantity takeoff		Quantity takeoff		Quantity takeoff		Quantity takeoff	
Tabulation		Tabulation		Tabulation		Tabulation	
Project cashflow monitoring and control							
Setting up monitoring system		Setting up monitoring system		Setting up monitoring system		Setting up monitoring system	
Gathering construction information		Setting up model		Setting up model		Setting up model	
Update construction schedule		Gathering construction information		Gathering construction information		Gathering construction information	
Generate mark up plan		Update construction model		Update construction model		Update construction model	
Quantity take-off		Generate mark up plan		Generate mark up plan		Generate mark up plan	

Tabulation for payment claim		Quantity take-off		Quantity take-off		Quantity take-off	
Gathering document from subcon		Tabulation for payment claim		Tabulation for payment claim		Tabulation for payment claim	
Tabulation for payment response		Gathering document from subcon		Gathering document from subcon		Gathering document from subcon	
		Tabulation for payment response		Tabulation for payment response		Tabulation for payment response	
Company cashflow monitoring and control							
Setting up monitoring system		Setting up monitoring system		Setting up monitoring system		Setting up monitoring system	
Gathering construction information		Setting up model		Setting up model		Setting up model	
Update construction schedule		Gathering construction information		Gathering construction information		Gathering construction information	
Quantity take-off		Update construction model		Update construction model		Update construction model	
Tabulation for payment claim		Quantity take-off		Quantity take-off		Quantity take-off	
Gathering document from subcon		Tabulation for payment claim		Tabulation for payment claim		Tabulation for payment claim	
Tabulation for payment response		Gathering document from subcon		Gathering document from subcon		Gathering document from subcon	
Input to financial system		Tabulation for payment response		Tabulation for payment response		Tabulation for payment response	
Verification and monitoring		Input to financial system		Input to financial system		Input to financial system	
Cashflow summary		Verification and monitoring		Verification and monitoring		Verification and monitoring	
		Cashflow summary		Cashflow summary		Cashflow summary	