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FINAL REPORT

Project Title:

(English) Evaluation of Impact of Policy Interventions on the Building Information Modelling (BIM) Adoption Status in the Hong Kong Construction Industry: From a Comparative Perspective

(Chinese) 評估政策介入對香港建造業建築信息模擬技術採用現狀的影響：基於比較研究視角

Principal Investigator (PI): Professor Li Heng

Institution: The Hong Kong Polytechnic University

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Executive Summary

I.Abstract of the Research

i. Chinese

基於准自然試驗設和組態設計，本研究旨在採用比較研究視角評估香港地區首個建築資訊模擬技術（BIM）強制性政策對建造業的影響，並採用組態視角識別和比較導致BIM 不同的採納率的條件配置及差異。通過對香港地區 2015-2021 年期間 502 家企業應用 BIM 項目的面板數據的調研，應用傾向得分匹配雙重差分(PSM-DID)方法評估了政策介入對項目績效的促進效果。同時基於技術-組織-環境（TOE）框架,以 38 家大型企業（LOs）和 36 家中小型企業（SMOs）為案例，運用模糊集定性比較分析方法，識別技術、組織、環境條件對不同規模組織 BIM 採納水準的組態效應及其路徑選擇。本研究形成了多項研究成果，旨在為推動 BIM 技術在香港建造業的擴散及發展提供政策指導及啟示：

(1) 關於 BIM 強制政策對項目績效的促進效果，基於 PSM-DID 的分析結果表明：①BIM 強制政策有效提升了項目的主觀 BIM 績效和投資回報率，為本地建造業的發展提供了實質性支援。②動態分析結果顯示，政策介入對項目績效的促進作用隨著時間的推移逐漸增強，呈現出明顯的動態性。 ③比較不同類型及規模的企業的 BIM 相關項目績效，研究表明政策效果的異質性非常顯著。具體而言，針對三類利益相關者，業主方 BIM 應用項目的績效升幅最高，承包商次之，但政策介入對設計諮詢方的促進作用並不顯著；針對不同規模的企業，政策介入對大型企業 BIM 應用項目的績效提升的影響最顯著，中小型企業次之，其中小型企業 BIM 應用項目績效受政策介入的影響反而出現小幅度下降。以上研究結果表明，BIM 強制政策的推行在促進香港地區建造業的發展的同時，也在一定程度上加劇了兩極分化，小型企業面臨被邊緣化的風險。

(2) 基於 74 個案例的定性比較分析結果表明：①高 BIM 採納率的必要條件不能由單

一條件構成，而是由技術、組織和環境三方面條件共同作用的結果。②跨案例比較分析結果表明，LOs 同 SMOs 的高 BIM 採納的實現路徑存在明顯差異。相對而言，LOs 中組織高層對於 BIM 應用的支持是實現高 BIM 採納率的重要條件，組織財務能力和組織自身 BIM 能力對 SMOs 實現高 BIM 採納率更為重要。③ 通過進一步分析組態條件之間的互動關係發現，在特定情境下，LOs 的組織財務能力和技術感知易用性可以相互替代；而 SMOs 的組織 BIM 能力在特定情境下能彌補組織在財務能力方面所面臨的限制。以上研究結果表明，組織的 BIM 採納實踐具有“多因一果”的特點，構成高 BIM 採納的條件組態具有多樣性，並在 LOs 和 SMOs 的條件配置方面存在差異性。

基於上述實證分析結果，本研究提出了四方面的政策建議，以推動 BIM 在香港建造業的全面實施，並給政府及相關機構日後制定策提供多元組合化建議。

ii. English

Based on the quasi-natural experiment combined with configuration perspective design, this study aims to evaluate the impact of the first BIM mandatory policy on the Hong Kong construction industry from a comparative lens, further identify and compare the combinations of conditions as well as the difference in conditions that lead to various BIM adoption rate from a configuration perspective.

Using the panel data of BIM-based projects of 502 organizations in Hong Kong during 2015-2021, the propensity score matching-difference in differences (PSM-DID) method is employed to evaluate the promotion effect of policy interventions on project performance. Meanwhile, on the basis of the Technology-Organization-Environment (TOE) framework, this research selects 38 large organizations (LOs) and 36 small and medium-sized organizations (SMOs) as cases to explore the configurational effect of technological, organizational, and environmental conditions on the adoption level of BIM in organizations of different sizes and their path choices by using fuzzy set qualitative comparative analysis (fs QCA).

Several research findings are obtained from this study, which aims to provide policy guidance and implications to promote the diffusion and advancement of BIM technology in the Hong Kong construction industry.

(1) Regarding the promotion effect of BIM mandatory policy on project performance, the results based on the PSM-DID analysis indicate that ① BIM mandatory has effectively improved the BIM subjective performance and BIM revenue on investment (ROI) of targeted projects, bringing substantial benefits for the development of the regional construction industry. ② According to the analysis results of the dynamic effect, the promotion effect of the policy intervention on the project performance gradually increases over time, showing explicit dynamics. ③ By comparing the BIM-based project performance across different types and sizes of organizations, this study indicates that the heterogeneity of policy effect is strongly significant. In detail, as for the three kinds of organizations (i.e. owners, design consultants, and contractors), in BIM-based projects, the owner achieves the largest increase in performance improvement, followed by the main contractor. Nevertheless, the promotion effect of the policy intervention on the design consultant is not significant. In terms of organizations of different sizes, policy intervention has the most significant impact on the BIM-based project performance of LOs, followed by SMOs, among which the BIM-based project performance of small organizations shows a slight decline after policy intervention. The research findings above show that while implementing the BIM mandatory policy has promoted the development of the construction industry, it has also exacerbated the

polarization to a certain extent, with small organizations facing the risk of being marginalized.

(2) The results of the qualitative comparative analysis based on 74 cases indicate that ① a single necessary condition cannot achieve a high BIM adoption rate; instead is the outcome of the configuration effect of technological, organizational, and environmental conditions. ② The cross-case comparative analysis results show a significant difference between configurational paths that lead to the high BIM adoption in LOs and SMOs. By contrast, the organizational top management support of LOs for BIM application is essential for achieving a high BIM adoption rate. The organizational financial capacity and BIM capability are more critical for SMOs to enhance BIM application practice. ③ Further analysis of the interaction between different conditions suggests that the organizational financial capacity and perceived ease of use of LOs can be substituted for one another in a given situation. In comparison, the organizational BIM capability can make up for the financial constraint faced by SMOs in a specific situation. The above results present that the BIM adoption practices of organizations are characterized by “multiple causes resulting in the same outcome,” and the combinations of conditions that result in high BIM adoption are diverse. There are apparent differences in the configurations of LOs and SMOs.

Based on the above empirical results, this study provides several policy implications and proposes some policy recommendations for the government and related organizations on diversified policy portfolios to facilitate the deep application of BIM in the Hong Kong construction industry.

II.Layman Summary on Policy Implications and Recommendations

i. Chinese

（1）針對建築資訊模擬技術（BIM）強制政策評估的異質性分析表明，BIM 強制政策大幅度提升了大型企業應用 BIM 的項目績效，但在一定程度上限制了小型企業應用 BIM 的行為；與此同時，定性比較分析結果表示，構成大型企業和中小型企業高 BIM 採納率的條件組態存在明顯差異。這意味著現行政策可能並不能覆蓋或使全部企業受惠，具體表現為中小型企業在強制政策的干預下，BIM 應用實踐仍不甚理想。本研究認為，未來有必要繼續擴大 BIM 相關政策的覆蓋範圍，將政策制定的焦點從"項目"適當向"組織"傾斜，根據不同規模的企業及其 BIM 應用實踐和組織特徵制定差異化的政策，並在現有政策基礎上增加激勵和幫扶性政策。具體而言，可以根據本研究識別出的 9 種 BIM 高採納率配置推出一系列組合型政策，以滿足建造業利益主體的差異化需求，進一步完善 BIM 應用實踐及提高 BIM 應用項目績效。多管齊下以鼓勵廣泛採用創新建築方法及科技，進一步促進生產力、提高建造質素。

（2）實證結果表明，靈活利用學習槓桿，做好知識的有效管理是促進 BIM 成功實施的關鍵。針對中小型企業案例的定性比較分析發現，組織的 BIM 能力可以在特定情況下替代財務能力從而實現 BIM 的高採納率。基於此，為提升香港地區建造業中 BIM 的應用率，本研究建議政府機構積極開展有關先進建築科技的課程及活動，強化創新技術知識管理，為相關企業的從業人員提供專業技術培訓，同時指導企業建立開展內部交流以實現學習成果的有效轉化。政府亦可以鼓勵企業與本地高校建立合作關係，積極吸納有望投身建造業的專才。

（3）實證結果亦表明，強制性政策對項目績效的作用在不同利益主體及不同規模的企業中呈現明显的異質性，對於大型企業和業主企業 BIM 應用實踐的

提升具有明顯促進作用，而對設計咨詢企業及小型企業帶來的積極影響則十分有限。這可能會加深建造業中不同企業對 BIM 認知的差異以及加劇 BIM 應用的不平衡趨勢。為緩解該趨勢的負面影響，消除現時業界對 BIM 應用的障礙，本研究建議政府可以通過建立交流平臺及鼓勵合作機制以培養、支援建造業中創新應用相對落後的企業的 BIM 應用能力。一方面，本研究建議政府可以通過建立 BIM 交流平臺，鼓勵擁有成熟 BIM 應用實踐經驗的建築及工程業界專業人士分享經驗，展示 BIM 應用的實踐成果，以強化現階段較為落後的企業對於 BIM 的認知；同時可以針對 BIM 應用能力較為落後的企業定期舉辦相關的創新技術知識及技能比賽，進一步促進企業之間的經驗交流與技術學習。另一方面，本研究同時建議政府推出鼓勵中小企業間跨組織合作的獎勵機制，鼓勵中小型企業形成以項目為導向的 BIM 技術互補聯盟，推動中小企業更廣泛的應用 BIM 技術，從而進一步促進 BIM 相關知識在香港建造業的擴散，最終使得建造行業內不同的企業都能受惠於此項創新技術。

（4）政策評估的動態性分析表明，政策干預對試點 BIM 項目績效的促進作用呈現動態逐年增加的趨勢；而異質性分析則發現政策干預帶來的促進作用並沒有覆蓋建造項目的全部參與方，設計諮詢方及小型企業受惠較少。因此，政府機構在今後實施相關政策時，可以同時建立相應的政策評估體系。具體而言，本研究認為可以根據政策目標制定評價指標，通過比較視角建立政策長動態期追蹤機制，在政策實施過程中定期進行調研並分階段收集業界的反饋意見，以更好地評估政策的有效性。通過不斷提升政策與參與方的適配度，促進 BIM 在香港建造業的整體發展，藉以持續改善本港建造業質素。

ii. English

(1) The heterogeneity analysis of the BIM mandatory policy evaluation shows that the BIM mandatory policy has significantly improved the project performance of large enterprises in applying BIM, but to a certain extent has restricted the behavior of small enterprises in adopting BIM; meanwhile, the results of the qualitative comparative analysis indicate that there is a significant difference in the composition of conditions that constitute the high BIM adoption rate of large enterprises and small and medium enterprises. This indicates that the current policy may not cover or benefit all enterprises, Specifically, the practice of BIM application in small and medium-sized enterprises is still not very satisfactory under the intervention of mandatory policies. This study suggests that in the future, it is essential to continuously expand the coverage of BIM-related policies, and tilt the focus of policy formulation from "projects" to "organizations" appropriately. The government is also suggested to formulate differentiated policies according to different sizes of enterprises and their BIM application practices as well as the organizational characteristics. And provide incentives and supportive policies on the basis of existing policies. Specifically, a series of combined policies can be introduced based on the nine BIM high adoption rate configurations identified in this study, to meet the differentiated requirements of organizations in the construction industry. Thus further improving BIM application practices and enhancing the performance of BIM application projects. The multi-pronged approach will encourage the widespread adoption of innovative construction methods and technologies to further promote productivity and improve construction quality.

(2) The empirical results indicate that the flexible use of learning levers and effective knowledge management is the cornerstone to promote the successful implementation of BIM. The qualitative comparative analysis of SMOs cases revealed that an organization's BIM capabilities can be substituted for financial capabilities in specific situations to achieve high BIM adoption rates. Based on this, in order to enhance the adoption rate of BIM in the construction industry in Hong Kong, the government agencies are recommended to actively launch courses and activities on advanced construction technologies, strengthen knowledge management of innovative technologies, provide professional technical training to practitioners of relevant enterprises, and guide enterprises to establish internal communication to realize the effective transfer of learning outcomes. The government can also encourage and assist enterprises to establish partnerships with local universities to actively recruit professionals who are expected to join the construction industry.

(3) The empirical results also indicate that the impact of BIM mandatory policy shows obvious heterogeneity among different stakeholders and organizations of different sizes. It has an obvious effect on the improvement of the BIM application practice of large organizations and owners, meanwhile, the design consultants and small organizations are not well-positioned to benefit from the positive effects of mandatory BIM policy implementation. This trend may deepen the discrepancy of BIM awareness among different stakeholders and exacerbate the uneven trend of BIM application in the construction industry, and further hinder the general adoption of BIM in Hong Kong. To mitigate the negative impact of this trend and eliminate the existing barriers to BIM application in the industry, the government is suggested

to establish a communication platform and encourage the collaboration mechanism to facilitate the BIM capability of companies that are relatively backward. On the one hand, this study suggests that the government can establish a BIM communication platform for professionals in the construction and engineering industry with mature BIM applications to share their experiences, demonstrate the practical results of BIM application to strengthen the knowledge of BIM for companies that are relatively lagging at the present stage. At the same time, the government is also suggested to hold regular BIM-related innovative technical knowledge and skills competitions to further promote experience exchange and technical learning among companies. On the other hand, this study also recommends that the government should provide an incentive mechanism to encourage cross-organizational collaboration among SMOs as well as encourage them to form project-oriented BIM technology complementary alliances to promote the wider application of BIM technology among SMOs. Thereby further facilitating the diffusion of BIM-related knowledge in the Hong Kong construction industry, and ultimately enabling different companies in the construction industry to benefit from this innovative technology.

(4) The dynamic analysis of the policy evaluation suggests that there is a dynamic year-on-year increase in the contribution of policy interventions to the performance of BIM-based projects. However, the heterogeneity analysis found that the policy interventions did not cover all parties involved in the construction projects, while the design consultants and small enterprises benefited less. Therefore, government agencies are encouraged to establish a corresponding policy evaluation system when implementing relevant policies in the future. Specifically, this study suggests that

evaluation indicators can be developed based on policy objectives, and a long-term dynamic tracking mechanism can be established through a comparative perspective, as well as conduct regular investigations and collect feedback from the industry in phases during the policy implementation process to better evaluate the effectiveness of policies. By continuously enhancing the policy and participant's adaptability, facilitate the overall development of BIM in the regional construction industry, so as to consistently improve the quality of Hong Kong's construction industry.

1. Introduction

The construction industry worldwide has long been criticized for its slowness to adopt innovative technologies and processes to address the performance problems of cost overruns, schedule delays, and quality inferiorities. As an innovative technology to parametrically model and integrate the design, construction, and operation information throughout the project lifecycle, Building Information Modeling (BIM) has been widely recognized as a solution to many performance problems rooted in traditional design and construction processes. Like many other innovative technologies in the construction domain, BIM is a systemic innovation, with its successful implementation in a construction project generally requiring the close collaboration of multiple organizations. Based on its distinct characteristic of using parametric objects to model and manage project information, BIM can be used in a variety of areas such as clash detection, sustainability analysis, cost estimation, construction scheduling, and offsite fabrication throughout the project life cycle (Eastman, Eastman, Teicholz, Sacks, & Liston, 2011; T. Hartmann, Gao, & Fischer, 2008). It is widely claimed that BIM if implemented appropriately, can facilitate a more integrated design and construction process and generate substantial benefits in terms of fewer design coordination errors, more energy-efficient design solutions, reduced production cycle time, lower construction cost, and higher design and construction productivity (Bryde, Broquetas, & Volm, 2013; D. Cao, Li, & Wang, 2014; D. Cao et al., 2015; Gao & Fischer, 2008). Based on case studies in the USA and Canada, for example, it is estimated that BIM has the potential to reduce unbudgeted change orders by 37%-48% (Giel & Issa, 2013) and increase onsite labor productivity by 75%-240% (Poirier, Staub-French, & Forgues, 2015). As such, it is even claimed by Hill (2008) that BIM is driving "the most transformative evolution the construction industry has ever experienced."

Knowing the potential benefits of BIM in addressing performance problems in traditional design and construction processes, governments or their executive arms in many regions have released relevant policies to facilitate the adoption and implementation of BIM in their construction industry. Table 1 summarized the BIM initiatives (i.e., policies, strategies, standards, and guidelines) as well as the BIM adoption targets developed in 7 countries/areas grouped into Asia, Europe, and the United States.

Table 1. BIM Policies and Adoption Status in Different Regions

Region	**Countries or Agencies**		**BIM Policies or Strategies**	**BIM Adoption Targets**
The United States	Nation-wide	General Service Administration (GSA) the United States Army Corps of Engineers (USACE) National Institute of Building Sciences (*NIBS*)	In 2006 the GSA mandated the use of BIM in new buildings designed through its Public Buildings Service in and after Fiscal Year 2007. The *NIB*S has developed a building information modeling (BIM) guide for building owners	Require BIM on projects
	State-wide	State governments such as	Since 2009, local governments in many states began to mandate the use of BIM in state public projects.	Require BIM on projects

		Wisconsin, Texas, Ohio, etc.		
Europe	the United Kingdom	BSI, CIC, AEC-UK, and Cabinet Office	In 2011 the Cabinet Office mandated that all central government departments adopt Level 2 BIM (collaborative 3D BIM with all project and asset data being electronic) in their projects by 2016	Adopt Level 3 BIM by 2020
	Denmark	Danish Enterprise and Construction Authority (DECA)	In 2007 the DECA initiated the Digital Construction Program (DCP) which aims to set requirements for the use of information technologies including BIM in public projects.	Danish state clients mandate BIM in all projects
	Sweden	Transportation Administration (TA)	In 2015, all investment projects are mandated to use BIM	Mandate the use of BIM in all investment projects by 2015
Asia	Singapore	Building and Construction Authority (BCA)	In 2011 the BCA released a BIM roadmap mandating the use of BIM in all projects with more than 5000 m^2 by 2015.	Mandate the industry using BIM and BIM e-submission
	Japan	MLIT, JFCC, JIA	2010, MLIT mandated BIM in government projects	JIA mandates BIM in government projects
	Mainland China	The Ministry of Housing and Rural-Urban Development	2012, the government released the National 12th Five-Year Plan (2011-2015)	2016, the government released the National 13th Five-Year Plan (2016-2020)

The aforementioned regions have seen rapid BIM adoptions in the past decade benefit from the established policies and related supporting measures. According to the Smart Market Survey in 2012 and the National Building Specification (NBS) International BIM Survey in 2015, for example, the adoption rate of BIM among industry practitioners reached 71% in the USA in 2012 (Bernstein et al., 2012) and 78% in Denmark in 2015 (NBS 2016). The lasted National Building Specification (NBS) reported that due to the effects of statuary policies, BIM usage increased by 12% in 2018 worldwide (NBS 2018). Figure 1 summarizes the latest situation of BIM application in the representative regions. It can be seen that the application of BIM in the above-mentioned regions has made different and considerable progress.

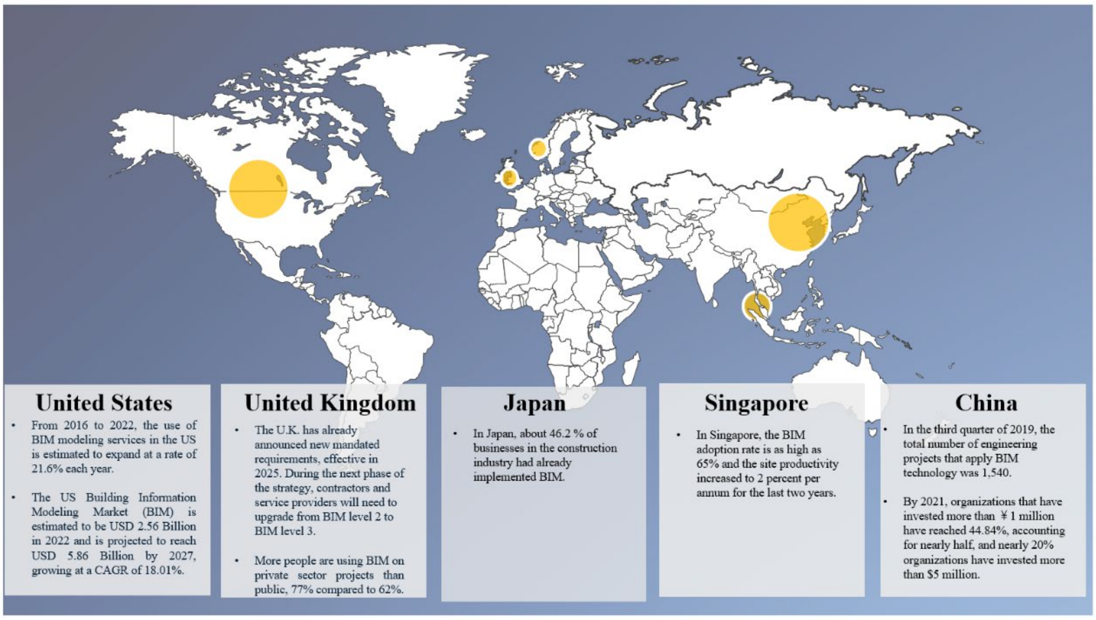

Figure 1: Status Quo of BIM Application in the Representative Regions

Source of Data: ADVENSER (2022), Research and market (2022), René Morkos (2022), David Bain (2022), Ministry of Housing and Urban-Rural Development of the People's Republic of China(2019), Report on BIM Application in China's Construction Industry (2021)

Hong Kong is one of the pioneering regions globally to advocate and facilitate BIM development in the construction industry officially. While the deployment of BIM in Hong Kong could date back more than a decade ago, when pioneered by some public client organizations such as the Housing Authority, the adoption of BIM in Hong Kong is still not widespread compared with leading practices worldwide. According to a survey conducted by the Hong Kong Polytechnic University (PPR Project No.: 2016.A6.075.17A.), less than 10% of the investigated corporates already involved in

BIM adoption practices are implementing BIM in more than 50% of all their projects during 2016-2017, which is substantially lower than the similar rates reported in the UK (NBS 2017) and Shanghai (COHURDM 2017). And as stated in the "BIM Adoption Survey 2019" published by CIC, the organizations that do not have active BIM projects account for 56% of more than 700 surveyed organizations, and only 9% are identified as the BIM leaders which are defined as substantially more proactive in using BIM can more readily realize benefits from their BIM use. (CIC,2020). And with regard to the spread of BIM implementation practices among different types of industry organizations, the development of facilitating such innovative technology is uneven. For example, smaller-sized design and construction organizations are generally implementing BIM at lower levels in the local construction industry. As a result, on 1 December 2017, the Development Bureau (DEVB) issued a Technical Circular (Works) No. 7/2017 on the Adoption of BIM for Capital Works Projects in Hong Kong. It is stated in the circular that capital works projects with a project estimate of more than $30 Million shall use BIM technology since 1 January 2018.

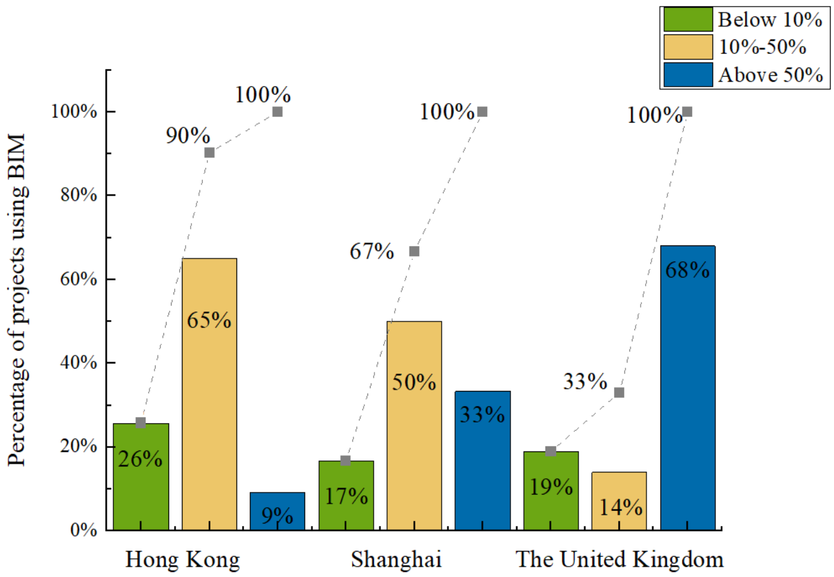

Figure 2 Comparison of the Proportion of Projects Utilizing BIM among Surveyed Organizations in Hong Kong, Shanghai, and the UK

Besides the BIM initiatives taken by the public sector including policy, guidelines, and standards throughout the past decade, the first governmental mandatory BIM policy has been enacted for more than 5 years. It is time to assess the impacts of this policy by answering the following questions. (1) Whether this policy has produced intended impacts? (2) Is there any room for improvement, or are there any remedial measures for statuary bodies to take?

In this research project, the research team aims to provide a systemic summary of BIM initiatives taken by the public sector and examine how the public policy impacted the BIM adoption and implementation practices in the Hong Kong construction industry. In view of the specific characteristics of Hong Kong's construction industry and its BIM implementation practices, specifically, this research project adopted the Propensity Score Matching and Difference-In-Difference (PSM-DID) method to compare the BIM adoption behavior among organizations before and after the public policy was released and use the case-based approach to understand how organizational BIM adoption/implementation practices have been influenced by this public policy. As stated in the application proposal, the detailed objectives of this research project are as follows:

1) To investigate and summarize the relevant BIM initiatives taken by the public sector in the Hong Kong construction industry;

2) To illustrate and compare BIM adoption behavior among organizations in the Hong Kong construction industry before and after the implementation of mandatory policy;

3) To recommend strategies to facilitate the diffusion of BIM among organizations in Hong Kong based on the propensity score matching difference-in-difference analysis and qualitative comparative analysis result.

The remainder of this research report is organized as follows. The next section first summarized a series of BIM policies in Hong Kong and provides the theoretical background of the policy intervention on project performance, and the theoretical basis of comparative perspective on the institutions of different natures or sizes in the construction industry. The following two sections have elaborated on the impact of mandatory policies on the project and organizational levels respectively, including the empirical data collected in the Hong Kong construction industry, the measurements used to operationalize the constructs related to the research model, and the data analysis processes and results. Section 5 discussed the policy implications of the research findings while Section 6 concluded the related output of this project.

2. Theoretical Background and Research Model

2.1 Status Quo of BIM Application and Related Initiatives in the Hong Kong Construction Industry

While governments in the aforementioned regions have established plans for the mandatory use of BIM in certain types of projects (Cao et al. 2014; Cheng and Lu 2015), the development of BIM in Hong Kong during the past decade was primarily driven by the market itself. Therefore, the diffusion of BIM in the Hong Kong construction industry was still at a preliminary stage and is considered to be lagging behind those pioneering regions (CIC, 2014).

The use of BIM in Hong Kong's construction industry can date back more than a decade. The Hong Kong Government has been aggressively introducing new BIM policies starting from 2009. However, the BIM adoption rate is still unsatisfactory. According to survey studies conducted by the Construction Industry Council in 2019 and 2020, more than 70% of the main contractors and sub-contractors are not implementing BIM. The survey study in 2020 states that enhancement of communication is rated as the most significant impact of BIM adoption in Hong Kong while various issues are raised, for example, the mix of open/proprietary file formats, information uncertainty, and the need for high-value data/information. Knowing these problems, the public sector in Hong Kong has been formulating and implementing relevant policies/standards/guidances over the past decade.

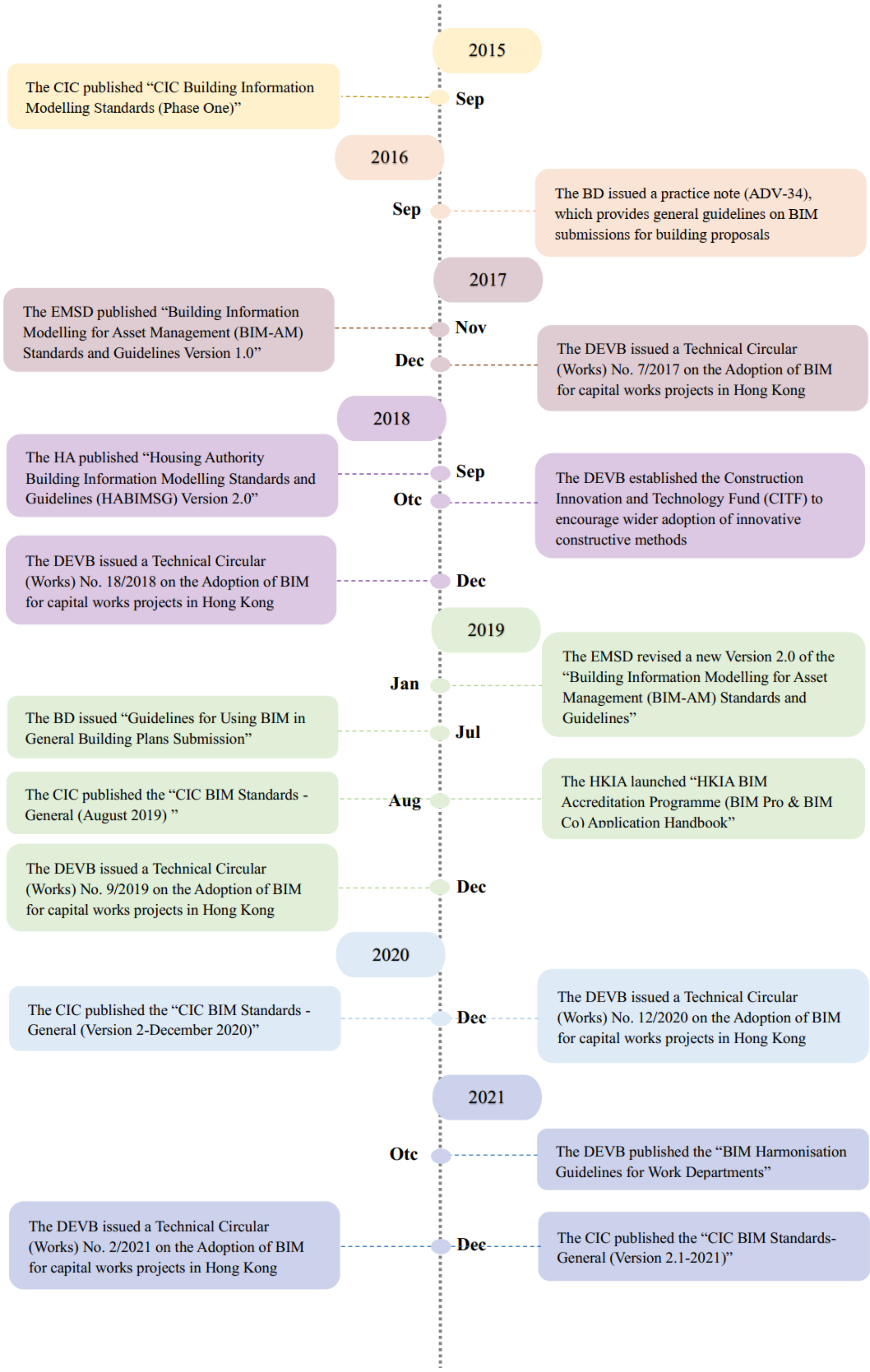

Figure 3 BIM-Related Policies and Initiatives in Hong Kong

As illustrated in Figure 2, this study has systematically reviewed the initiatives conducted by the government and its affiliated bodies from a longitudinal perspective. Specifically, DEVB has developed a BIM road map for the enhancement of BIM uses from fundamental BIM uses in project management at design and construction stages to more sophisticated BIM uses on digital fabrication and asset management which, for the technical circular released in 2020, it specifies that all tenders for construction contracts are required to use BIM technology for "Digital Fabrication" which is to use BIM technology to facilitate the fabrication of mass customized components or off-site prefabricated assemblies and the BIM models can also be used for prototyping with 3D printers as part of a design intent review process.

In conclusion, the construction industry in Hong Kong is obviously lagging behind the leading practices countries in BIM implementation, and the adoption of BIM in regional construction remains at a primary stage. Meanwhile, concerning the spread of BIM implementation practices among different types of industry organizations, the development of facilitating such innovative technology in Hong Kong is uneven.

2.2 The Effect of Policy Intervention on the Performance of Innovation Applications

Innovative policy initiatives can be conceptualized in three key dimensions (Bristow and Healy, 2014): the institutions through which policy actors act, i.e., the patterns and structures of governance (Bodin and Crona, 2009); the types of policy interventions which has been taken (Chaminade and Esquist, 2010); and the magnitude or timing of policy interventions (Bovaird, 2014). There is a growing literature on the classification of policy interventions, but few studies are scarce to understand the policy interventions of innovation for the performance of organizations (Evans *et al.*, 2017; Jiao and Boons, 2014). As an innovative technology, an increasing number of scholars are aware of the importance of BIM policy research (Li *et al.*, 2017). However, the current research on the relationship between policy intervention and BIM performance is almost completely disconnected.

On the one hand, some research has examined the policy efforts of different countries or regions in promoting BIM adoption in construction industries, including the specific form and content of BIM policies (Yang and Chou, 2018). Lee and Borrmann (2020) stated that the government and its subsidiary authorities had played a key role in requiring and promoting the adoption of BIM in construction projects. From a holistic view, BIM policies range from a firm mandate of BIM in all public projects through legislation changes, where necessary, to providing financial and organizational assistance down to lower levels of encouragement and support (Kassem and Succar, 2017).

With respect to the research on BIM policy in Hong Kong, Wong *et al*. (2011) discussed BIM adoption initiatives in the Hong Kong public sector, compared the implementation of BIM in Hong Kong and the U.S., and provided some suggested strategies for implementing BIM in Hong Kong. Oti-Sarpong *et al.* (2020) critically examined the implications of and responses to government policies and initiatives guiding mandatory BIM use for all public projects in the Hong Kong construction industry through content analysis. Both of the research has pointed out that the current policies implemented in Hong Kong have the potential to exacerbate the fragmentation of BIM adoption in the Hong Kong construction industry.

In response to the impact of mandatory policies, the above studies focused on changes in BIM adoption at a national or regional scale and reached an agreement that BIM adoption has all achieved milestone improvements following mandatory policy implementation (Lee and Borrmann, 2020). However, Dainty *et al.* (2017), from the specific standpoint of the small firm, critiqued the implementation of these mandatory policies, arguing that the BIM-centered political reform agendas might not stimulate innovation on a larger scale but rather disenfranchise small firms that are unable (or unwilling) to participate, thereby creating a polarized market in which benefits accrue mostly to those already privileged and the less powerful are marginalized (Cushman and McLean, 2008). Regrettably, their theoretical arguments are not supported by empirical evidence.

On the other hand, a separate part of the research focuses on successful cases of BIM application and the impact of BIM on projects, exploring the benefits that can be derived from implementing BIM in the project (Olanrewaju *et al.*, 2022; Jaaron *et al.*, 2022). Smits *et al*. (2017) compared the BIM benefits of BIM-based projects and non-BIM projects with similar functional areas at a semiconductor manufacturing company. The results showed that BIM positively impacted cost and time performance, further evidence the positive value of BIM on project performance. Bryde *et al.* (2013) reported BIM benefits based on the secondary data from 35 construction projects that utilized BIM and concluded that improved cost performance due to BIM was most frequently mentioned, closely followed by time, communication, coordination, and quality benefits. Yang and Chou (2018) analyzed the application practices of BIM in the Taiwan construction industry. The result revealed that the most obvious benefit of implementing BIM is to improve the design quality of construction projects. These conclusions about the BIM benefits have also been validated in other case studies (Alshawi and Ingirige, 2003; Becerik-Gerber and Rice, 2010; Azhar, 2011).

In addition to the case studies mentioned above, some other studies used questionnaires to directly ask participants about their attitudes toward their organization's project performance to obtain participants' subjective evaluations of BIM performance (Becerik-Gerber and Rice, 2010). A similar approach is adopted in an increasing number of empirical studies on BIM performance. For example, Smits *et al*. (2017) used this method to examine the relationship between BIM maturity and project performance. Xu *et al*. (2022) examined the impact of contractual flexibility on BIM-enabled project performance during the construction phase.

Another aspect of research on BIM performance focuses on the BIM return on investment (BIM ROI) from a quantitative perspective (Olanrewaju *et al.*, 2022; Sompolgrunk *et al.*, 2023), presenting BIM performance with relatively objective data through the cost-benefit analysis. The return on investment analysis compares the expected (or realized) benefits of an investment against the cost of the investment (i.e., ROI = benefit/cost) (Azhar, 2011). According to a survey by McGraw Hill Construction, two-thirds of BIM users have achieved positive ROI on their overall investment in BIM (McGraw Hill Construction, 2009). Becerik-Gerber and Rice (2010) analyzed the cost structure of BIM implementation and pointed out that the cost of software, software upgrade, hardware, hardware maintenance, and BIM training are the main components of BIM investment. Azhar (2011) reported the ROI of 10 BIM-assisted projects in Holder Construction that was continuously measured in 2006, with results ranging from 229% to 39,900%. However, Azhar (2011) argued that the actual BIM ROI might be higher because the results do not concern indirect design, construction, administrative, or other cost savings. In 2012, Autodesk developed a calculation model to reveal the first-year ROI of BIM application in the design phase, considering the system cost, labor, training, and productivity changes (Autodesk, 2012). The variables used in the formula include the cost of hardware and software ($), monthly labor cost ($), training time (months), productivity lost during training (%), and productivity gain after training

(%). Given the differences in BIM application contexts and the different investment and revenue structures, a uniform calculation standard still needs to be developed. However, it should be noted that the ROI calculated in this report is the BIM return, not the project's return on investment.

2.3 The Configurational Perspective on the Influencing Factors of BIM Adoption

In past decades, many pieces of research have been published exploring influential factors to the success of BIM adoption. Considering the complexity of construction projects and the diversity of the context, an increasing number of scholars employ Tornatzky *et al*. (1990)'s technology–organization–environment (TOE) framework to divide these factors into three categories, technological factors, organizational factors, and environmental factors (Ahuja *et al.*, 2016; Chen *et al.*, 2019; Qin *et al.*, 2020; Wang *et al.*, 2022; Yuan *et al.*, 2019). Thus, based on the existing empirical evidence on the use of the TOE framework in BIM adoption, a systematic literature review of these three dimensions was conducted for further construction of the research framework of this study.

2.3.1 Technological Factor

Perceived usefulness and perceived ease of use are two primary technological considerations of BIM adoption (Yuan *et al.*, 2019). According to Davis's technology acceptance model (TAM), organizations decide to adopt BIM due to the various benefits brought by this technology (Davis, 1989). Perceived benefits of using BIM in construction projects are critical drivers in BIM adoption (Lee *et al.*, 2015), especially for SMOs, and are often used to explain the perceived usefulness of BIM (Davis *et al.*, 1992). Given that perceived ease of use may not vary significantly across different technologies, this part mainly reviews the perceived benefits of BIM to facilitate an understanding of the technological factors influencing BIM adoption. According to the literature, these benefits can be categorized into the following four groups: improving scheduling (Azhar *et al.*, 2012; Bryde *et al.*, 2013; Hong *et al.*, 2019; Li *et al.*, 2019; Wang *et al.*, 2022), controlling cost (Babatunde *et al.*, 2020; Chan *et al.*, 2019; Wang *et al.*, 2022), enhancing collaboration (Chan *et al.*, 2019; Georgiadou, 2019; Lu and Korman, 2010; Wang *et al.*, 2022), and improving quality (Ahuja *et al.*, 2016; Doumbouya *et al.*, 2016; Papadonikolaki, 2018; Wong *et al.*, 2011).

Regarding time efficiency, BIM was proven to lead to real-time scheduling of activities, faster design processes, and potentially on-time delivery (Ahuja *et al.*, 2016; Almuntaser *et al.*, 2018; Blanco and Chen, 2014). For example, the data management module helps to execute the tasks related to quantity surveying quickly and automatically adjust any changes (Steel *et al.*, 2012). A BIM-based project can easily track production with support from schedules based on interoperable data sharing and help optimize construction sequencing, diminishing and avoiding delays (Grilo and Jardim-Goncalves, 2010).

When it comes to the cost saving, compared to the traditional 2D or 3D CAD application, BIM has more advantages in updating, maintaining, storing, and sharing data and could provide more accurate information (Georgiadou, 2019), thus reducing the risk of making a decision based on assumptions from outdated drawings (Arayici *et al.*, 2011; Barlish and Sullivan, 2012; Bryde *et al.*, 2013), thereby avoiding the corresponding financial loss. While on the other hand, some scholars emphasized that BIM performs very well in lean construction (Arayici *et al.*, 2011; Eastman *et al.*, 2011; Sebastian, 2011; Volk *et al.*, 2014; Weygant, 2011). Effective collaboration and information sharing can improve the design and thus reducing added costs in material supply and human resources (Eastman *et al.*, 2011; Volk *et al.*, 2014), and the risk of costly rework can also be eliminated (Sebastian, 2011; Weygant, 2011).

Enhancing collaboration is one of the most vital benefits mentioned in existing studies. As we all know, the construction project is quite complex as it requires frequent communication and tight collaboration between many stakeholders (Murguia *et al.*, 2021). However, based on a shared set of standards and a common data environment, BIM can help to facilitate a novel and effective integrated collaborative approach based on a shared set of standards and a common data environment (Farnsworth *et al.*, 2015; Sebastian, 2011). BIM's ability to update models in real-time helps exchange project information easily, thus contributing to effective communication and conflict resolution throughout the project lifecycle (Blanco and Chen, 2014). The study conducted by Hong *et al*. (2020) indicates that most organizations adopt BIM to solve collaboration problems.

In addition, BIM technology is also widely praised for its positive effect on quality improvement. According to a previous study, many organizations have adopted BIM to achieve better project quality worldwide (Wong *et al.*, 2011). In the design phase, adopting BIM allows designers to save time in drafting and leave more time for designing, thus leading to better design quality (Li *et al.*, 2019). And in the construction phase, BIM's ability to generate comprehensive information and model concerning the building components can help modular building contractors increase quality output (Eastman *et al.*, 2011). Besides, with BIM, a construction project can be inspected during all stages of the project (Crotty, 2012), and conflicts and clashes between the building and its elements can be detected in real-time (Azhar *et al.*, 2012; Babatunde *et al.*, 2020), which provides great technical assurance for project quality improvement.

2.3.2 Organizational Factors

BIM adoption is related to inter-organizational processes and practice (Faisal Shehzad *et al.*, 2022). Introducing BIM technology into construction projects means substituting the traditional workflow (Zahrizan *et al.*, 2013); it is not just a matter of changing software tools; instead, it is a matter of re-engineering the firm and transforming its business process and management practices (Al-Ashmori *et al.*, 2020; Arayici *et al.*, 2011; Saka and Chan, 2020). In this sense, BIM adoption can be regarded as an organizational change (Eastman *et al.*, 2011). It includes top management's decision-making and requires related organizational capabilities to change the workflows (Al-Ashmori *et al.*, 2020). As evident in previous studies, top management support (Abbasnejad *et al.*, 2021; Ahuja *et al.*, 2016; Arayici *et al.*, 2011), financial capacity (Belay *et al.*, 2021; Hochscheid and Halin, 2020), and BIM capability (Cao *et al.*, 2017; Ding *et al.*, 2015; Hong *et al.*, 2019; Ozorhon and Karahan, 2017) are the top three crucial organizational factors that strongly relate to BIM adoption.

The positive impact of top management support on BIM adoption has been examined in a series of research (Ahuja *et al.*, 2016; Arayici *et al.*, 2011; Chen *et al.*, 2019; Mom *et al.*, 2014; Okakpu *et al.*, 2018). From a practical level, adopting and implementing BIM within the organization involves managing people, shifting organizational culture, deploying resources, and changing the business process and workflows (Arayici *et al.*, 2011; Saka and Chan, 2020). Usually, the decision on the above matters is in the hands of the top management. Just as Gledson and Greenwood (2017) argued, BIM adoption was an authority-type decision made by upper organizational management with innovation awareness. Thus, the success of BIM adoption in organizations can be attributed to the support from top management.

There is no doubt that the adoption of BIM requires a high investment in purchasing software and hardware and staff training (Eadie *et al.*, 2013). Organizations with substantial financial support are more likely to adopt BIM and vice versa. Recently, some researchers have examined the effect of organization size on BIM adoption behavior and found that the substantial difference in BIM adoption rates was attributed to the financial capacity of the organization, where larger organizations have more financial resources. This significantly contributed to the adoption rate of BIM in large firms (Saka and Chan, 2022). For SMOs, a lack of financial capacity often results in shying away from BIM (Abanda and Tah, 2014; Benjaoran, 2009; Hanna *et al.*, 2013; Juan *et al.*, 2017). More specifically, because of financial constraints, they may be more concerned with the cost of applications and training for the employee when deciding whether to adopt BIM.

Regarding organizational BIM capabilities, a series of researches indicate a deep relationship between BIM adoption and organizational BIM capability, which strong BIM capability usually leads to the successful adoption of BIM (Ghaffarianhoseini *et* *al.*, 2017; Ozorhon and Karahan, 2017; Zhang *et al.*, 2020; Zhao *et al.*, 2018). To be specific, on the one hand, the organization staff's capability to operate and maintain BIM tools and files will contribute to the establishment of an organizational knowledge-support system, which makes it easier to use BIM in construction projects (Hong *et al.*, 2019). On the other hand, a wealth of BIM knowledge helps organizations better understand the benefits of BIM, thus increasing the likelihood of adoption (Hosseini *et al.*, 2016).

2.3.3 Environmental Factors

Environmental factors are the conditions outside of the organizations that influence organizational BIM adoption behaviors in the form of institutional isomorphism (Cao *et al.*, 2014; Faisal Shehzad *et al.*, 2022; Saka *et al.*, 2022). In line with the institutional theory (DiMaggio and Powell, 1983), BIM emerged as a nascent technology, and the institutional environment organizations embed will inevitably influence their adoption behavior. A considerable amount of literature has been published on the relationship between BIM adoption and the institutional environment in the construction management field (Cao *et al.*, 2014; Ma *et al.*, 2019; Murguia *et al.*, 2021; Saka *et al.*, 2022; Zhang *et al.*, 2020). It has been reported that institutional pressures from the government, clients, and competitors are the most significant push factors for BIM adoption (Adriaanse *et al.*, 2010; Ahuja *et al.*, 2016; Babatunde *et al.*, 2020; Chen *et al.*, 2019; Ding *et al.*, 2015; Papadonikolaki, 2018; Saka *et al.*, 2022).

Concerning the government pressure, Liu *et al.* (2015) regarded the BIM adoption behavior as a national issue with an emphasis on the formal acceptance by policymakers to be globally competitive. In this sense, BIM adoption is a product of political will or legislation and requires related policies, regulations, and guidelines to bring it into effect (Olugboyega and Windapo, 2019). Several studies have shown that government pressure strongly contributes to BIM adoption rates in many countries (Babatunde *et al.*, 2020; Belay *et al.*, 2021; Wang *et al.*, 2022).

As evident from prior research findings, BIM adoption is emerging as a contract requirement for many projects as clients increasingly demand it (Adriaanse *et al.*, 2010; Gurevich and Sacks, 2020; Saka and Chan, 2022). On the one hand, to enhance the ability to secure more contacts and maintain the relationship with their client base (Manley, 2008; Sexton and Barrett, 2003), organizations will cater to their clients' demand for BIM. While on the other hand, the government, as a unique client, has begun to require public facility agencies to adopt and implement BIM in the business processes to promote BIM technology diffusion (Cheng and Lu, 2015).

In consideration of competition, when organizations find that their competitors are using BIM, especially the industry leaders, they will also consider adopting BIM into projects to maintain a competitive advantage in the marketplace (Faisal Shehzad *et al.*, 2022; Hochscheid and Halin, 2020; Saka *et al.*, 2022). It can be seen that building organizational competitiveness has become one of the primary concerns in the BIM adoption decision (Cao *et al.*, 2018; Ding *et al.*, 2015; Hong *et al.*, 2019).

2.4 Summary

In summary, the current research findings provide a comprehensive understanding of the effect of policy intervention on innovation performance as well as the influencing factors for BIM adoption. In particular, the TOE framework has provided a diverse understanding of the influential factors of BIM adoption in different dimensions. However, scant attention has been paid to the combinations of various factors that may lead to a high BIM adoption, which is derived from an emerging configurational perspective based on the set logic (Rihoux *et al.*, 2011). Under the framework of set theory, it is a combination of conditions (independent or "explanatory" variables) rather than a single condition that eventually produces the outcome. There are usually several combinations of conditions resulting in the same outcome, while the given condition may have a different impact on the outcomes given the different contexts (Rihoux *et al.*, 2011). Given this, the configurational view advocated by set theory challenges the single linear relationship that has been the focus of traditional regression analysis and is expected to provide a new explanation for the enabling mechanism of BIM adoption. As an emergent technology, BIM adoption in organizations is complicated (Li *et al.*, 2019), involving numerous factors from technology, organization, and environment. In this sense, BIM adoption is the outcome of a combination of conditions rather than a given condition. Therefore, this study attempts to investigate the effective combinations of conditions that lead to a high BIM adoption in organizations based on the TOE framework and provide new insights into BIM adoption research from a configuration perspective. Based on this, the research framework of this study is constructed. As shown in Figure 4, the technological factors refer to the perceived ease of use and perceived usefulness, which include four potential benefits of BIM, namely improving scheduling, controlling cost, enhancing collaboration, and improving quality. Organizational factors refer to the organizational capabilities required for an organization to adopt BIM, including the three dimensions frequently appearing in the existing literature, namely top management support, financial capability, and BIM capability. Environmental factors refer to external pressure from the outside of organizations, including government pressure in the forms of a mandatory policy, competitor pressure from the market, and client contract pressure from the client.

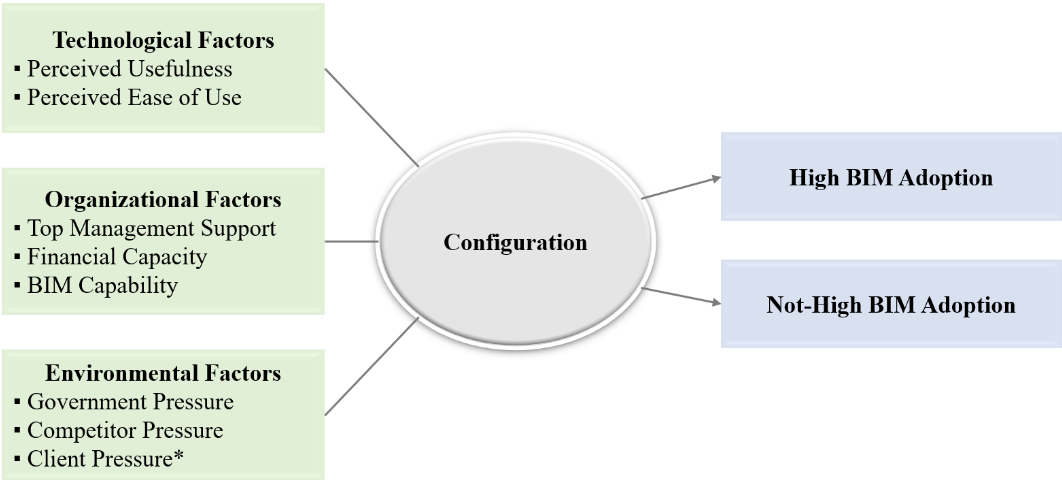

Figure 4 The Research Framework of Quantitative Comparative Analysis on BIM Adoption Behavior

Note: In line with the results of the interviews, client pressure was removed in the data analysis because there was a large overlap between government pressure and client pressure, according to the respondents' statements, most of the client pressure came from the mandatory policy.

As mentioned above, BIM adoption is the outcome of a combination of conditions rather than a given condition. Compared with conventional descriptive statistics and correlation analysis, fuzzy-set qualitative comparative analysis (fsQCA) is more applicable to the research question of this study. Proposed by Ragin (Ragin, 1987, 2000, 2008), QCA is a case-oriented method based on set theory and Boolean algebra (Ragin, 2008b; Schneider & Wagemann, 2012), which enables the researcher to define cases as sets of qualitatively derived causal attributes to determine causal pathways by comparing sets of cases with shared attributes and outcomes while using Boolean algebra to identify configurations that reflect the necessary and sufficient conditions for an outcome of interest. The core idea of QCA is causal complexity (Ragin, 1987);

multiple causes result in the same outcome, and causal relationships between condition and outcome are asymmetric (Ragin, 2008; Fiss, 2011). That is to say, it is often a combination of conditions rather than one single condition that leads to an outcome (Fiss et al., 2011; Rihoux et al., 2011). Thus, by identifying different configurational paths to a given outcome, QCA enables in-depth analysis of the research question in configurational terms and can identify the complex complementary and substitutive linkages among conditions, thus identifying the combinations of causal conditions that lead to high/low BIM adoption level. Finally, the comparative analysis between different cases (or paths) can provide more effective and suitable strategic suggestions for the government and related sectors.

Therefore, this research first implemented Propensity Scores in conjunction with Difference in Differences models (PSM-DID), particularly investigating a propensity score weighting strategy that weights the four groups (defined by time and intervention status) to be balanced on a set of organizational characteristics. And then explored the impact of the mandatory policy which influences organizations with different attribute/ownership types, and further combined with the potential adjustment of BIM implementation practices (i.e., BIM implementation areas, BIM implementation motivations, organizational strategies, etc.) from a quantitively comparative analysis approach, thus to comprehensively detect the performance of organization under the mandatory policy.

As illustrated in Figure 5, the research activities of this project have been categorized into four stages: research design, data collection, data analysis, and strategy development. In order to achieve the three proposed research objectives (i.e., investigation of BIM initiatives and comparison of BIM adoption behavior, case-oriented analysis, strategy assessment, and development), this project implemented semi-structured interviews and questionnaire survey as the data collection method and used the PSM-DID analysis and qualitative comparative analysis as the data analysis methods. Specifically, the research framework is displayed in Figure 5, and important steps are elaborated on in the subsequent sections.

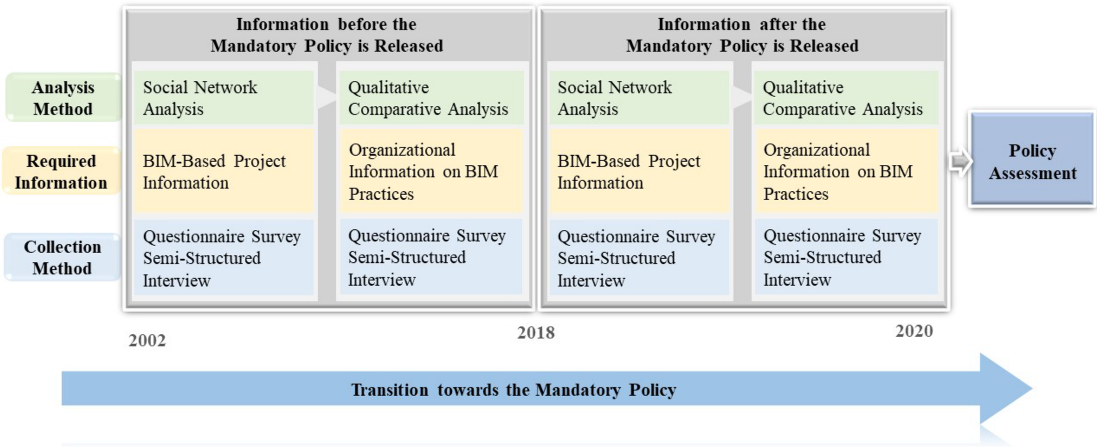

Figure 5 Process of Data Collection and the Designated Method

3. Exploring the Impact of Mandatory Policy on BIM-Based Project Performance

3.1 Research Methodology

3.1.1 Data Collection

Considering the characteristics of the industry structure and BIM adoption practices in the Hong Kong construction industry, the questionnaire was deployed to collect data on BIM-based projects and organizational BIM adoption practices. In order to assess the impacts of the mandatory policy on BIM implementation and practices in the regional construction industry, data has been collected in two separate groups. One group is the yearly data related to the public projects of the organizations which are affected by the mandatory policy, i.e., the data of the treated group. The other group is the yearly data related to the privacy projects of organizations, which are not affected by the mandatory policy (i.e., the control group). In view of data availability and sample size, this study identified two time periods to observe the time-changing trend of BIM-based project performance: data from 2015-2017 and data from 2018-2021. The questionnaire has been dispatched to the three target groups (i.e., owners, design consultants, and main contractors) to collect data on organizational BIM adoption/implementation practices in each group. In detail, the questionnaire survey was conducted with BIM directors, technical managers, or other informed professional individuals in these organizations due to their relatively high familiarity with BIM projects.

The research team initially distributed 800 questionnaires and finally received 585, among which 502 were valid questionnaires with an effective recovery rate of 62.75%. Descriptive statistics of variables are shown in Table 2.

Table 2. Demographic Information of Samples

Variable	Category	N	%
Organization Role	Main contractor	194	38.65
	Design consultant	138	27.49
	Owner	170	33.86
Organization Size	Large	156	31.08
	Medium	162	32.27
	Small	184	36.65
Organization Ownership	Multi-national	176	35.06
	Local	326	64.94
Organization Age	Under 10 years	58	11.55
	10-50 years	321	63.94
	50-100 years	94	18.73

Note: Large-sized organization refers to which employ more than 250 full-time employees, medium-sized organization refers to which employ 50-250 full-time employees, and small-sized organization refers that employs fewer than 50 full-time employees; Organization age refers to the years counting since the organization's establish year to the year of 2022.

3.1.2 PSM-DID Approach

Difference-in-difference (DID) method is commonly used to evaluate the effect of a policy (Stuart *et al.*, 2014). By comparing changes over time in a group affected by the policy intervention (treated group) to the group unaffected by the policy intervention (control group), unbiased effect estimates can be obtained. In general, the application of the DID method usually needs to satisfy the common trend assumption, that the difference between the two groups should be sufficiently small. However, according to the convergence theory and the BIM practice, this assumption is often challenging to be satisfied. The treated and control groups may differ in ways that their trends were affected, or the compositions may change over time, which leads to selective bias problems and decrease the precision of the estimate.

Realizing the selective bias in DID method, Heckman *et al*. (1997, 1998) combined the PSM method (Rosenbaum and Rubin, 1983, 1985) with DID method. Based on observable variables, the treated and control groups' samples were selected and matched to control the selective bias of samples to ensure the sample satisfied the assumption of a common trend for the DID analysis. Therefore, this study employed the PSM-DID method to examine the impact of the first mandatory BIM policy on the BIM-based project performance in the Hong Kong construction industry. By comparing the performance difference between the treated and control group before and after the policy was issued, this study has explored the net impact caused by the policy. The following section has described the use of PSM in conjunction with DID model, particularly investigating a propensity score weighting strategy that weights the four groups (defined by time and intervention status) to be balanced on a set of characteristics.

Propensity Score Matching (PSM)

The PSM method was proposed by Rosenbaum and Rubin (1983,1985) to calculate the propensity score to match the counterfactual results of the treated group. The primary approach is to find an individual "j" in the control group without policy intervention and make such a "j" is as similar as possible to the observable variables of the individual "i" in the treated group with policy intervention, i.e., $\chi_i \approx \chi_j$. Therefore, propensity scores are often also defined as distance functions of covariates to estimate the probability of an individual being affected by policy intervention. The PSM in this study includes the following five steps. Firstly, referring to Caliendo and Kopeinig (2008), this study selected the variables that may simultaneously affect the outcome variable and the participation decision of samples from the existing literature as covariates. Based on this, BIM implementation experience, BIM adoption rate, the depth of BIM implementation level, organization size, and the years of organization establishment were selected for the propensity score estimation.

Afterward, this study selected the logit model (Cox, 1970) to estimate the propensity scores, which can be calculated based on the following equations (Eq. (1), Eq. (2), Eq. (3)). Assuming Bpi belongs to the treated group, the conditional probability of Bpi entering the treated group can be calculated. Where p_i denotes the probability that Bpi is assigned to the treated group under the condition of a series of covariates χ_i. Thus, $\mathrm{logit}(p_i)$ in Ep. (1) is a 0-1 variable, which is 1 when the Bpi is in the treated group;

otherwise is 0. Through binary logit regression on Ep. (1), the estimated value of the parameter $\hat{\beta}$ and $\widehat{\beta_0}$ can be obtained. Then, the propensity score $\widehat{p_i}$ can be calculated through the estimated parameter values based on Eq. (3).

$$\text{logit}(p_i) = \log\left(\frac{p_i}{1-p_i}\right) = \beta_0 + \sum \beta_i \chi_i + \varepsilon_i \tag{1}$$

$$p_i = p(Bp_i = 1|\chi = \chi_i) \tag{2}$$

$$\widehat{p_i} = \sum \hat{\beta} \chi_i + \widehat{\beta_0} \tag{3}$$

Then, referring to Austin (2010), this study used the nearest-neighbor matching within specified calipers to match the treated and the control groups according to the propensity score. On the one hand, referring to Abadie and Imbens (2006), this study set the ratio as 1:4, i.e., matching four samples from the control group for each sample in the treated group, to ensure a smaller sample variance. After matching, this study examined the quality of the matching by common trend test and balance test in the following steps. And Stuart and Rubin (2008) suggested that matching with replacement can yield better matches and decrease the bias. On the other hand, this study used a caliper of width equal to 0.2 of the standard deviation of the logit of the propensity score as this value can minimize the bias due to the measured confounders and result in optimal estimation (Austin, 2010, 2011).

The last step is to diagnose the matching quality. In general, there are two central properties that the propensity score model should always be assessed and reported: the balance property and the common support region. This study used two approaches to test the balance. One is to compare the standardized difference of group propensity score means (Stuart, 2010). The other one is to use the t-test to check if there are significant differences in covariate means for both groups (Rosenbaum and Rubin, 1985). As for the common support assumption, this study examined the range of the propensity score distributions in the treated and control group with a visual analysis of the density distribution of the propensity score in both groups to determine whether the two groups' propensity distributions sufficiently overlap.

Differences in differences (DID)

The DID method is a common quasi-experimental approach to estimating the causal effect of a specific policy (Zang *et al.*, 2020). Specifically, the Hong Kong government launched the first BIM mandatory policy can be regarded as an exogenous policy intervention on the BIM adoption behavior of organizations at a particular time point and deemed as a quasi-natural experiment in the construction industry (Stuart *et al.*, 2014). Since the policy was issued in early 2018, this study took that year as the time node and set the virtual variables as follows. The BIM-based project (Bp) represents the project virtual variable and defines the two-dimensional virtual variable, Bp = {0, 1}. Bp = 1 represents the treated group, i.e., the BIM-based public projects of organizations affected by the first BIM mandatory policy during 2018-2021. Bp = 0 represents the control group, i.e., the BIM-based privacy projects of organizations unaffected by the policy during 2018-2021. As for the time virtual variable, time = 1 represents the period after the implementation of the first BIM mandatory policy, i.e., 2018-2021. Time = 0 represents the period before implementing the first BIM mandatory policy, i.e., 2015-2017. In order to estimate the net impact of the first BIM mandatory policy on the BIM-based project performance, this study constructed the following equation (Eq. (4)):

$$Perf_{it} = \beta_0 + \beta_1 Bp_{it} + \beta_2 time_{it} + \beta_3 Bp_{it} * time_{it} + \beta_4 \chi_i \quad (4)$$

where $Perf_{it}$ denotes BIM-based project performance, i and t denote the i-th BIM-based project and t-th year, respectively. β denotes the regression coefficients. Bp_{it} denotes project virtual variables. $time_{it}$ denotes time virtual variables. The interaction item $Bp_{it} * time_{it}$ denotes whether the first BIM mandatory policy has been implemented. χ_{it} denotes control variables. ε_{it} denotes random disturbance term.

3.1.3 Model Development

Dependent Variable

The BIM-based project performance was designated as the dependent variable in this study. Recently, the benefits of BIM on project performance have been widely discussed by scholars (Azhar, 2011; Suermann, 2009; Becerik-Gerber and Rice, 2010; Barlish and Sullivan, 2012; Bryde *et al.*, 2013; Doumbouya *et al.*, 2016; Smits *et al.*, 2017; Franz and Messner, 2019; Kim *et al.*, 2021). Among them, cost, time, quality, communication, and return on investment (ROI) are the top five indicators to determine performance improvement in delivering BIM-based projects. Therefore, these five most frequently referred indicators were used in this study to measure BIM-based project performance. All the questions set answers on a 7-point scale. As for the ROI, it is important to note that the calculated ROI rate is an estimated payback of BIM, i.e., BIM return on investments (ROI), not a return on investment in a specific project. Referring to Reizgevičius *et al*. (2018), this study constructed a calculation formula based on "Autodesk Revit" ROI calculations (see Eq. (5))

$$\boldsymbol{BIM\ ROI} = \frac{(Benefits\ from\ BIM - based\ projects - Investment\ in\ BIM)}{Investment\ in\ BIM} \qquad (5)$$

where investment in BIM includes the purchase of software and staff training. The specific value is yearly.

<u>Independent Variable</u>

The implementation of the first BIM mandatory policy in the Hong Kong construction industry can be regarded as a quasi-natural experiment. Just as illustrated above, a BIM-based project (Bp) is a policy dummy variable, including whether a project is affected by the policy. For BIM-based public projects, the value of Bp is set to 1. For BIM-based privacy projects, the value of Bp is set to 0. Time is time dummy variable representing the implementation of the first BIM mandatory policy. The value of time is set as 1 for years after the implementation, i.e., 2018-2021. The value of time is set as 0 for years before the implementation, i.e., 2015-2017. And in DID model, as shown in Eq. (4), the interaction term $Bp_{it} * time_{it}$ is the difference-in-differences estimator, the coefficient of $Bp_{it} * time_{it}$ reflects the net impact of the policy on the BIM-based project performance.

Control Variables

Based on the existing literature and the unique characteristics of BIM-based projects, this study selected the BIM implementation experience, BIM adoption rate, the depth of BIM implementation level, organization size, and the years of organization establishment as control variables to ensure the stability of the estimated results. Specifically, in the same way as a lot of research before (Zang *et al.*, 2020; Yu *et al.*, 2021), covariates and control variables are the same.

(1) BIM implementation experience (denoted by "BIMexp") is measured by the total years of the BIM application practices.

(2) BIM adoption rate (denoted by "BIMado") is measured by the ratio of the number of projects using BIM against the number of overall projects.

(3) Depth of BIM implementation level (denoted by "BIMdep") is measured by the status of BIM implementation referring to "*CIC BIM Standards - General (Version 2.1 - 2021)*".

(4) Organization age (denoted by "lnage") is measured by the natural logarithm of the years of organization establishment.

(5) Organization size (denoted by "lnsize") is measured by the natural logarithm of the yearly number of full-time employees in the organization.

3.2. Empirical Analysis and Results

3.2.1 PSM Analysis Results

The BIM implementation experience (BIMexp), BIM adoption rate (BIMado), BIM implementation depth (BIMdep), organization size (Orgsize), and organization age (Orgage) were first selected as covariates and then run in the PSM model to eliminate the differences in characteristics between projects as much as possible and to solve the sample matching problem in quasi-natural experimental studies. As for the organization size and age, this study took the natural logarithm of these two continuous variables to weaken heteroscedasticity in the analysis. This was followed by a logit model to estimate the propensity score, which is the conditional probability of accepting the policy intervention, to further weaken the self-selection problem. And then, the K-nearest neighbor matching method is conducted on PSM. Referring to Abadie and

Imbens (2006), this study set the ratio as 1:4, i.e., matching four samples from the control group for each sample in the treated group, to ensure a more minor sample variance. After matching, this study examined the quality of the matching by common trend test and balance test in the following steps.

Common Support Test

The common support assumption is a basic assumption that needs to be satisfied before conducting PSM-DID, i.e., judging whether the observations in the control group overlap the observations from the treated group. According to the statistical result of the quantity of treatment and control groups in a common support area as shown in Table 3. It is clear that out of 3514 observations, only 43 observations in the control group are not in the common support region, and 1757 observations in the treated group are all in the common support region. It can be judged that the assumption is satisfied in this study. These samples that fall outside the common support region are removed in subsequent analyses to better satisfy the common support assumption.

Table 3 Results of Common Support Test

Group	**Common support**		**Total observations**
	Off support	On support	
Control group	43	1714	1757
Treated Group	0	1757	1757
Total observations	43	3471	3514

Balance Test

A balance test is conducted in this section to judge the matching results' validity further. As shown in Table 4, after matching, the absolute values of the normalized bias of all covariates are less than 20%, which is considered valid for the matching estimation results according to the criteria proposed by Rosenbaum and Rubin (1985). Meanwhile, the t-statistics of all covariates are no longer significant, which indicates that there is no significant difference between the treated and control groups, and the new samples obtained using the PSM model can effectively solve the problem of sample selection bias. More robust estimation results can be achieved in the subsequent analysis. Furthermore, to straightforwardly show the matching results, the kernel density distribution maps before and after matching are plotted based on the propensity scores as illustrated in Figure 6. Combined with the overlap of the two kernel density curves, the difference between the two groups significantly decreases after matching, the overlap becomes significantly higher, and the overall tends to be a normal distribution, which indicates that the selection bias problem is effectively solved with PSM. Based on the above results, the matching results of this study passed the balance test.

Table 4 Balance Test of PSM

Variables	Sample	Mean		%bias	%reduct	*t*-test	
		Control	Treated		bias	t	P > |t|
BIMexp	Unmatched	6.9164	7.8936	50.1	97.6	13.51	0.000
	Matched	7.4288	7.4479	1.2		0.30	0.762
BIMado	Unmatched	0.2085	0.3366	70.2	91.9	20.81	0.000
	Matched	0.2697	0.2800	5.7		1.50	0.135
BIMdep	Unmatched	12.343	14.277	40.8	87.5	12.10	0.000
	Matched	13.168	13.408	5.1		1.26	0.208
lnage	Unmatched	3.5212	2.9857	80.9	97.7	21.95	0.000
	Matched	3.3526	3.3468	1.9		0.50	0.618
lnsize	Unmatched	6.2024	7.1028	40.8	98	11.93	0.000
	Matched	6.5456	6.7205	0.8		0.24	0.813

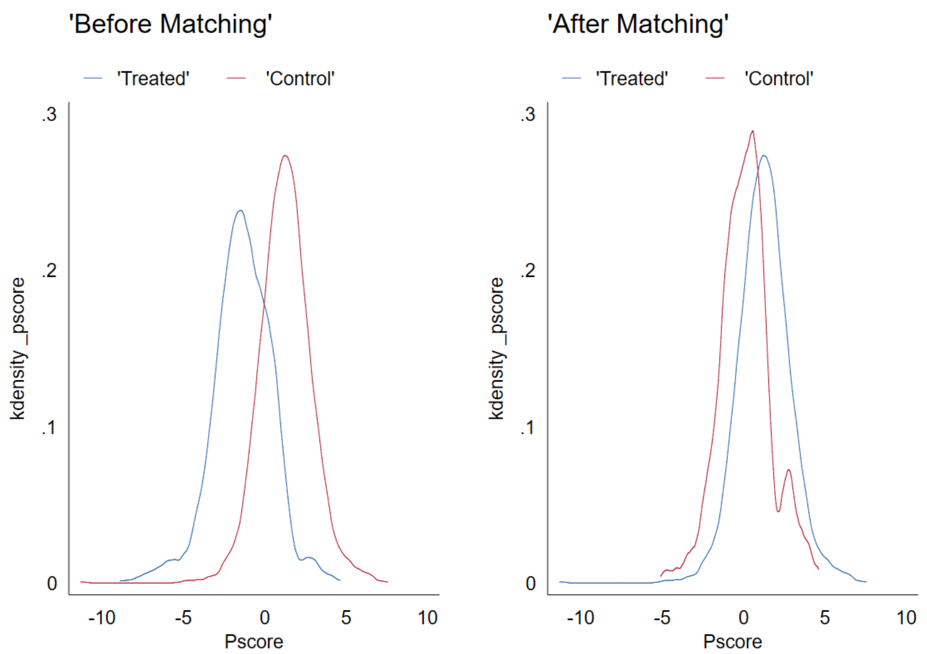

Figure 6 Kernel Density Curve of Propensity Score Before and After Matching

3.2.2 DID Regression Results

Parallel trend test

The parallel trend assumption is critical for the DID method (Guo *et al.*, 2020; Fu *et al.*, 2021; Gao and Yuan, 2021). Specifically, the treated and control groups should have similar time trends in BIM performance before the mandatory policies are in place. To verify this assumption, this study plotted the time trend graph of BIM performance between 2015 and 2022 for the treated and control groups in STATA software (see Figure 7). Regarding the trend lines for the treated and control groups, subjective BIM performance and BIM ROI show relatively similar trends before 2018. The time trends for both began to diverge after the policy was implemented. Therefore, the results of the above analysis support the parallel trend assumption.

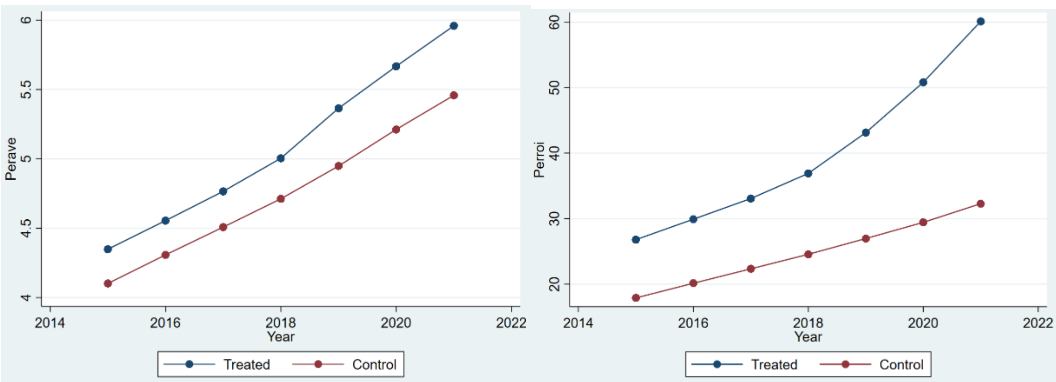

Figure 7 Trends of Explained Variables During 2015-2021

Main effects of the mandatory policy

The regression results for the intervention effects of the mandatory policy have been shown in Table 5, where column 1 (model 1) and column 2 (model 2) show the results for the impact of mandatory policy on subjective BIM performance, while column 3 (model 3) and column 4 (model 4) show the results for the effect of mandatory policy on BIM ROI. The results show that the coefficient symbols of the interaction terms (treated*time) of all four columns are positive and significant, which implies that mandatory policy has a significant impact on the subjective BIM performance and BIM ROI of projects in the treated group, regardless of whether other variables are considered. Further, the coefficient of the interaction term in column 2 is 0.1241, which is significant at the 1% level, while the coefficient of the interaction term in column 4 is 6.5493 and is also significant at the 1% level. This indicates that the impact of mandatory policy on BIM ROI is greater than subjective BIM performance. When interpreted in an economic sense, implementing the mandatory policy increased the subjective BIM performance level of projects in the treated group by an average of 12.41% and increased the BIM ROI level by 654.93%.

Table 5 The Impact of the Mandatory Policy on BIM Performance

Variables	**Perave**		**Perroi**	
	Model 1	Model 2	Model 3	Model 4
treated	0.2453***	0.1134***	9.4019***	6.3733***
time	0.7775***	0.5925***	8.2892***	7.2667***
treated*time	0.1649***	0.1241***	9.5348***	6.5493***
Control	No	Yes	No	Yes
Constant	4.3111**	3.7574**	8.3151**	7.4037**
R^2	0.2859	0.7449	0.0352	0.6682
N	3471	3471	3471	3471

Note: *p < 0.1, **p < 0.05, ***p < 0.01

The Dynamic Effect of the Mandatory Policy

In order to test whether the promotion effect of mandatory policy on BIM-based project performance has gradually increased with time, this study evaluates the dynamic effect of the policy. Referring to Zang *et al*. (2020) and Yu *et al*. (2021), this study selects the sample with one, two, and three years after policy implementation to generate new interaction terms that multiply the year dummy variables from 2019 to 2021 with the policy dummy variables ("treatments") for the PSM-DID regressions. The analysis result has been demonstrated in Table 6. As shown in column 6 the regression coefficients of the subjective BIM performance are 0.1274, 0.2575, and 0.3879 for 2019-2021, and all of them are statistically significant at the 1% level. This indicates the promotion effect of the mandatory policy on BIM subjective performance gradually increased over time. Regarding the BIM ROI, according to the results presented in column 8, the regression coefficients for 2019-2021 are 6.6567, 8.4891, and 11.6714, respectively. And all are significant at the 1% level, indicating a year-on-year growth trend of the impact of mandatory policy on BIM ROI.

Table 6 The Results of the Dynamic Effects of Mandatory Policy on BIM Performance

Variables	**Perave**		**Perroi**	
	Model 5	Model 6	Model 7	Model 8
treated*time19	0.1896***	0.1274***	9.5554***	6.6567***
treated*time20	0.4924***	0.2575***	13.2339***	8.4891***
treated*time21	0.7842***	0.3879***	22.5383***	11.6714***
Control	No	Yes	No	Yes
Constant	4.3696**	3.7634***	20.7482**	12.4498***
N	3471	3471	3471	3471
R^2	0.3295	0.7537	0.0427	0.6826

Note: $*p < 0.1$, $**p < 0.05$, $***p < 0.01$

Heterogeneity Test of Policy Effect

Given the differences in the adoption and implementation of BIM among various stakeholders and organizations of differing sizes, this study further divided the sample into separate groups based on their roles and organization size. To examine the impact of mandatory policy on different types of organizations. This section further conducts PSM-DID analysis for three stakeholders, namely, contractors, design consultant, and owner as well as three samples of the large, medium, and small organizations, respectively. According to the regression results provided in Table 7, it can be concluded that for different stakeholders, in terms of subjective BIM performance, the mandatory policy has a significant promotion effect on the owner ($\beta=0.2183$, $p<0.01$), followed by the contractor ($\beta=0.1055$, $p<0.01$). In contrast, the policy also had a boosting effect on the design consultants ($\beta=0.0298$), but the coefficient was not significant ($p>0.1$). Considering the BIM ROI, the mandatory policy exhibits similar heterogeneity effects on three types of stakeholders, with the most substantial boost for the owner ($\beta=16.3196$, $p<0.01$), followed by the contractor ($\beta=0.8543$, $p<0.05$) and design consultants ($\beta=1.7256$, $p>0.1$). As for different sizes of organizations, with regards to the subjective BIM performance, the mandatory policy has a significant promotion effect on both large and medium-sized organizations, with the strongest effect for large organizations ($\beta=0.3183$, $p<0.01$). However, for small-sized organizations, there is a negative effect ($\beta=-0.1158$, $p<0.01$). Regarding BIM ROI, the mandatory policy still has the strongest promotion effect for large-sized organizations ($\beta=19.9145$, $p<0.01$), followed by medium-sized organizations ($\beta=5.5076$, $p<0.01$), and a negative effect for small organizations ($\beta=-1.2657$, $p<0.01$). Overall, the effects of the mandatory policy are heterogeneous across different stakeholders and organizations of different sizes. Specifically, the promotion effect of mandatory policy on the BIM performance of different stakeholders is the strongest for the owner, followed by contractor and design consultants, and the effect of mandatory policy on the BIM performance of different size organizations is strongest for large-sized organizations, followed by medium-sized organizations and small ones.

Table 7 The Results of the Heterogeneity Test

Variables	**Different stakeholders**			**Different sizes**		
Treated*time	Owner	Contractor	Design consultant	Large size	Medium size	Small size
Perave	0.2183***	0.1055***	0.0298	0.3183***	0.1408**	-0.1158***
Control	Yes	Yes	Yes	Yes	Yes	Yes
Constant	2.1056***	3.1490***	2.6359***	4.5493***	2.7464***	2.2119***
R2	0.8003	0.8495	0.7461	0.8076	0.6216	0.8699
N	1189	1318	964	1168	1018	1285
Perroi	16.3196***	0.8543**	1.7256	19.9145***	5.5076***	-1.2657***
Control	Yes	Yes	Yes	Yes	Yes	Yes
Constant	49.7174***	3.2021***	6.6576***	16.3708***	26.1259***	10.5402***
R2	0.9069	0.9196	0.7634	0.6314	0.6063	0.6840
N	1189	1318	964	1168	1018	1285

Note: *p < 0.1, **p < 0.05, ***p < 0.01

3.3 Research Findings

This section employed the PSM-DID method to investigate the impact of the first mandatory policy on BIM adoption by the Hong Kong government on the BIM-based project performance of three key stakeholders in the construction industry, drawing the key conclusions as follows.

First, the implementation of the mandatory policy has significantly improved the performance of the BIM-based project in terms of subjective BIM performance and

BIM ROI and thus providing substantial support for the development of the construction industry in the region. Second, from a temporal perspective, the promotion effect of the mandatory policy on BIM-based project performance gradually increases year by year and exhibits a clear dynamicity. Both subjective BIM performance and BIM ROI of the treated group show a gradually increasing trend in the investigated period. Third, from a heterogeneous perspective, the impact of the mandatory policy shows significant heterogeneity across the three stakeholders and organizations of different sizes. Regarding the kinds of stakeholders, the policy has the strongest impact on owners' BIM performance, with contractors second. However, the promotion effect on the design consultants is not significant. These conclusions are in line with Reizgevičius et al. (2018) and Yang and Chou (2018), but are not consistent with the findings of Cao et al. (2015) on a Chinese sample. The aforementioned research concluded that the main beneficiaries of projects using BIM are design consultants and contractors. According to the BIM Adoption Surveys conducted by CIC, it is clear that there are significant differences in the BIM adoption rate and depth of BIM implementation among different stakeholders (CIC, 2020, 2021). Design consultants occupy a significant portion of the leaders in BIM adoption. In contrast to mandatory adoption under policy requirements, BIM adoption behavior of the design side is usually on their initiative. Therefore, the implementation of mandatory policies has little impact on them. At the same time, the Hong Kong BIM mandate allows organizations to subcontract for the demanded BIM use (DEVB, 2018), which gives design parties more opportunity to participate in construction projects as BIM subconsultants (Oti-Sarpong et al., 2020), further exacerbating the already high multilevel subcontracting typical of projects in the Hong Kong construction industry (Chiang, 2009). The increase in the number of subcontracts will undoubtedly dilute the promotion effect of the mandatory policy on the design consultants.

On the other hand, regarding the organization size, the policy has a positive impact on large-size organizations and medium-sized organizations, but a negative impact on small organizations. A series of the literature indicated that small organizations are not as active in BIM adoption (Hosseini et al., 2016; Dainty et al., 2017; Hong et al., 2019; Saka and Chan, 2020; Vidalakis et al., 2020). Specifically, small-sized organizations have to increase their investment with the adoption of BIM in order to respond to the policy requirement. However, compared with the organizations already equipped with leading practices, these organizations are founded to be not familiar enough with BIM and are less confident with their BIM skill (Georgiadou, 2019). At the same time, given the highly collaborative nature of construction projects, payback periods are generally lengthy, which makes the positive impact of the policy on small-sized organizations minimal and potentially more negative.

4. Exploring the Impact of Mandatory Policy on the Organizational Performance

4.1 Research Methodology

4.1.1 Data Collection

The data collection process in this section consisted of the following two parts, a semi-structured interview, and a questionnaire survey. First of all, this study compiled a list of SMOs that met the requirements of this study and conducted semi-structured interviews for three months, from September 2022 to December 2022, aiming to understand the BIM adoption status of these organizations. During this period, a total of 80 organizations were visited. After the deep analysis of the organization information, this study finally limited the case sample to 36 SMOs and 38 LOs that could cover different BIM adoption factors. These 74 organizations were invited to participate in a questionnaire survey on BIM adoption factors by email to obtain the quantitative data needed for this study. Before the data was gathered, two rounds of pilot tests were conducted, and the wording and the questionnaire format were improved based on the responses. Finally, 74 valid questionnaires were obtained for the next step of the QCA analysis. The Demographic information of investigated organizations has been demonstrated in the following Table 8.

Table 8 Demographic Information of Samples

Variable	Category	N	%
Organization Role	Main contractor	38	51.35
	Design consultant	21	28.38
	Owner	15	20.27
Organization Size	Large size	38	52.35
	Small and medium size	36	48.65
Organization Ownership	Multi-national	24	32.43
	Local	50	67.57
Organization Age	Under 10 years	8	10.81
	10-50 years	48	64.86
	50-100 years	12	16.23
	Above 100 years	6	8.1

Note: Organization age refers to the years counted from the organization's established year to the year 2022.

4.1.2 Data Measurement

This section uses established calculation formulas or descriptions from the existing literature to measure the BIM adoption level and related influencing factors with minor modifications based on the semi-structured interviews in the sampled firms.

(1) BIM adoption level: According to Young et al. (2007) and Jung and Lee (2016), this study uses the BIM adoption rate to measure the BIM adoption level of the firm, which is determined by the percentage of BIM-based projects among all the projects in

a firm. Respondents were asked to give an exact percentage for their BIM adoption level.

(2) Technological conditions: Consistent with the TAM, perceived ease of use and perceived usefulness are two critical dimensions to explain the technological conditions influencing BIM adoption. Perceived usefulness, also referred to as perceived benefits (Davis et al., 1992), highlights the attractive improvements achievable through BIM adoption as perceived by the SMOs (Hong et al., 2018), including improving scheduling, controlling cost, enhancing collaboration, and improving quality, which is measured with the questions "BIM always performs well in improving scheduling/ controlling cost/ enhancing collaboration/ improving quality." Perceived ease of use is measured with three questions adopted from Cao et al. (2014) and Gledson & Greenwood (2017) with the questions "It is easy to learn and on top of BIM" and "BIM is easy and skillful to use to handle work tasks" "In general, it is easy to use BIM."

(3) Organizational conditions: Organizational conditions include three dimensions. The scale of top management support was adapted from Premkumar and Roberts (1999), Ahuja et al. (2016), and Vigneshwar et al. (2022). It included two items. Specific questions include "Top management of this firm always provides supportive climate and resources for the adoption of BIM" and "Top management of this firm is highly interested in adopting BIM." At the same time, the scale of financial capacity was an

adaptation of Ahmed and Kassem (2018), Murguia et al. (2021), and Wu et al. (2021) and included two items. Specific questions include “This firm has sufficient funding for purchasing BIM-related equipment and software” and “This firm has sufficient funding for training BIM employees.” Last, the scale of BIM capability was adapted from Cao et al. (2017) and Vigneshwar et al. (2022) and included four items. Specific questions include “our team is experienced in implementing BIM,” “Our team is capable of solving the possible technical problems of BIM,” “Our team has the knowledge necessary for implementing BIM,” and “Our team is familiar with the benefits of BIM tools.”

(4) Environmental conditions: According to the results of the interviews, the Hong Kong government plays the same role in promoting BIM adoption in terms of mandatory policies and client demands; in other words, organizations receive most of the pressure from clients in the form of the mandatory policy. Therefore, this study focuses on the pressure from the government and competitors when measuring the environmental conditions affecting BIM adoption. This is consistent with Yang & Chou (2018), who emphasize that BIM adoption results from government and market drivers. The composite measures for these two dimensions were adapted and created based on prior studies (Chen et al., 2019; Wu et al., 2021). Two items measured the government pressure, and specific questions included “The decision about BIM adoption was influenced by the mandatory policy from the government,” “In the face of BIM adoption decision, mandatory policy from the government put much pressure on us.”

Two items measured the competitor pressure, and specific questions included "Whether competitors have adopted BIM influences the decision to adopt BIM in our firm," "In the face of BIM adoption decision, competitors' BIM adoption behaviors put much pressure on us."

Except for the BIM adoption rate, the questions were designed on 7-point Likert-type agreement scales, with the anchors from "strongly disagree" to "strongly agree." The descriptive statistics of each variable, correlations, and Cronbach's alpha are shown in Table 9. It can be seen that the values of Cronbach's alpha of the seven conditional variables are all greater than the threshold value of 0.7, indicating that the data in this study have a high degree of reliability.

Table 9 Descriptive Statistics, Correlations, and Cronbach's Alpha

Variables	**TPU**	**TPE**	**OTS**	**OFC**	**OBC**	**EGP**	**ECP**	**BAR**
TPU	0.855							
TPE	0.483***	0. 816						
OTS	0.457***	0.305**	0.892					
OFC	0.102	0.117**	0.632***	0.869				
OBC	0.455***	0.563***	0.301**	0.556***	0.926			
EGP	0.221*	0.198	0.111*	0.103	0.279*	0.855		
ECP	0.259**	0.146*	0.454**	0.395**	0.177*	0.108	0.787	
BAR	0.522***	0.433***	0.515***	0.404***	0.485***	0.322***	0.285***	--
Mean	5.56	5.01	5.56	5.35	5.69	5.65	4.88	0.44

SD	0.92	1.33	1.30	1.51	1.18	1.18	1.24	1.17
Min	3	2	3	2	3	3	3	0.1
Max	7	7	7	7	7	7	7	0.9

Note: N = 74; *p < 0.05, **p < 0.01, ***p < 0.001; the values of Cronbach's alpha are on the diagonal; TPU = perceived usefulness of the BIM technology; TPE = perceived ease of using BIM technology; OTS = organizational top management support; OFC = organizational financial capacity, OBC = organizational BIM capability, EGP = government pressure from the environment; ECP = competitor pressures from the environment, BAR = BIM adoption rate; same for the following.

4.1.3 Data Calibration

Calibration is the first and critical step in performing fsQCA (Ragin, 2008), which requires using theoretical and substantial knowledge to generate a fuzzy-set score relating to the degree of membership in a set (Ragin, 2008). To produce these scores, this study adopts the direct method of calibration to transform the conditions and outcome variables into different member sets (Fiss, 2011; Ragin, 2008). Considering that the conditions were measured by a 7-point Likert scale, this study refers to Ordanini et al. (2014) and Pappas et al. (2016), selecting 6, 4, and 2 as calibration anchors to calibrate the antecedent conditions in the SMOs sample, and draws on Mikalef & Pateli (2017), using 6, 4.5, and 3 as calibration anchors when calibrating the antecedent conditions in LOs sample. Regarding the outcome variable, the 95th, 50th, and 5th percentiles of the outcome were adopted as anchors to calibrate full non-membership, crossover membership, and full membership. Besides, aligned with the practice of Crilly et al. (2012), this study manually changes the value of affiliation from 0.5 to 0.499 instead of modifying all variable values to avoid cases with an affiliation of 0.5

being removed in subsequent fsQCA analysis. The calibration anchor points for the variable are shown in Table 10.

Table 10 Calibrations of Variables in SMOs and LOs

Variables	**Fully-in**		**Crossover**		**Fully-out**	
	SMOs	LOs	SMOs	LOs	SMOs	LOs
Conditions	6	6	4	4.5	2	3
Outcome	0.65	0.78	0.39	0.56	0.23	0.35

4.2 Analysis and Results

The data analysis in this study was carried out by the software fsQCA 3.0 (Ragin & Davey, 2016), including data calibration, construction of a truth table, necessity analysis, and sufficiency analysis.

4.2.1 Necessity Analysis

Necessity analysis is the foundation of configurational path analysis, which means that a condition always exists when an outcome occurs (Ragin & Fiss, 2008). Consistency is a critical indicator to check if there is a necessary or almost always necessary condition to lead to the outcome. Conventionally, the threshold of consistency score is 0.9 (Ragin & Fiss, 2008; Schneider, Schulze-Bentrop, & Paunescu, 2010; Misangyi et al., 2014). In this part, the necessity of the presence and absence of each condition for the presence and absence of the outcome were tested for both the large and small organization samples. As shown in Table 11, none of the conditions is necessary for a high or not-high BIM adoption because all the consistency scores are below the threshold of 0.9 (Ragin, 2008). This finding indicates that the high BIM adoption rate is caused by the combination of technological, organizational, and environmental conditions, not the effect of a single condition. It also shows that the differences in BIM adoption between LOs and SMOs come more from the combination of conditions than from a single condition. It makes sense to discuss the influence of configuration terms on the high level of BIM adoption.

Table 11 Analysis of Necessary Conditions

Conditions	**PRESENCE**				**ABSENCE**			
	Consistency		**Coverage**		**Consistency**		**Coverage**	
	SMOs	LOs	SMOs	LOs	SMOs	LOs	SMOs	LOs
TPU	0.75	0.51	0.89	0.89	0.41	0.49	0.17	0.48
~TPU	0.31	0.62	0.59	0.64	0.75	0.55	0.51	0.66
TPE	0.62	0.81	0.91	0.74	0.32	0.68	0.17	0.68
~TPE	0.43	0.32	0.63	0.63	0.83	0.56	0.44	0.66
OTS	0.68	0.78	0.88	0.88	0.41	0.58	0.19	0.63
~OTS	0.38	0.32	0.64	0.68	0.74	0.69	0.46	0.73
OFC	0.77	0.66	0.91	0.75	0.36	0.46	0.16	0.56
~OFC	0.33	0.49	0.59	0.59	0.80	0.66	0.51	0.64
OBC	0.65	0.51	0.92	0.93	0.32	0.56	0.16	0.62
~OBC	0.41	0.72	0.62	0.69	0.83	0.65	0.46	0.66
EGP	0.72	0.68	0.74	0.72	0.84	0.78	0.31	0.35
~EGP	0.33	0.62	0.85	0.58	0.30	0.76	0.28	0.82
ECP	0.53	0.62	0.86	0.61	0.40	0.39	0.23	0.36
~ECP	0.53	0.66	0.71	0.64	0.76	0.86	0.36	0.33

Note: The symbol ~ represents that the condition is absent or at a low level (at a low level, hereafter)

4.2.2 Sufficiency Analysis

Sufficiency analysis aims to reveal the logically possible and empirically occurring configurations of fuzzy sets (Greckhamer et al., 2008; Ragin, 2000, 2008). The configuration's explanatory strength in explaining the outcome's presence refers to the consistency scores of sufficiency (Fiss et al., 2013). Before conducting the standard analysis, the truth table was established based on the frequency and consistency thresholds. Referring to Ragin (2008) and Schneider & Wagemann (2012), the threshold of consistency was set as 0.75, and the threshold of frequency of cases per configuration was set as 2 (Fiss, 2011). Based on this, all configurations with a raw consistency above 0.75 and a proportional reduction in inconsistency (PRI) consistency above 0.7 were identified (Ragin, 2008). Table 12 shows five paths that point to high BIM adoption in SMOs and four in LOs. The values of the solution consisting of the SMOs sample and LOs sample are 0.88 and 0.91, respectively. Moreover, the consistency values of nine paths all exceed 0.75, which meets the minimum threshold Ragin (2008) suggested and can be regarded as sufficient. Besides, the solution coverage of high BIM adoption rate solutions in SMOs is 0.48, indicating that these combinations of conditions account for 48% of SMOs. Meanwhile, the solution coverage of 0.68 confirms that four solutions to the high BIM adoption account for 68% of LOs.

Table 12 Configurational Paths to High BIM Adoption in SMOs and LOs

Configurations	SMOs					LOs			
	SMH1	SMH2	SMH3	SMH4	SMH5	LH1	LH2	LH3	LH4
TPU	•	•	•			●			•
TPE			⊗	•	•		•		•
OTS	⊗	⊗	•	•	•	●	•	•	•
OFC	●	⊗	●		•	•		•	
OBC	⊗	●	•	•	•		•	•	
EGP	●	●	●	•			●	●	•
ECP				●	●				●
Raw coverage	0.16	0.16	0.16	0.15	0.22	0.20	0.38	0.42	0.24
Unique coverage	0.02	0.04	0.03	0.03	0.04	0.04	0.06	0.05	0.03
Consistency	0.78	0.82	0.78	0.78	0.82	0.91	0.94	0.86	0.85
Solution coverage	0.48					0.68			
Solution consistency	0.88					0.91			

Note: SMH1 = first configuration pointing to high BIM adoption in SMOs, while LH1 = first configuration pointing to high BIM adoption in LOs, same for other places; in line with Fiss (2011), the solutions are demonstrated by their condition structures: black circles indicate the presence of the condition; white circles with a cross mark indicate the absence of the condition; large circles indicate the core condition, which appears in both the parsimonious solution and the intermediate solution; small circles indicate the peripheral condition, which only appears in the intermediate solution; blank spaces mean "do not care"; same for the Table 5.

However, as shown in Table 13, only two configurations leading to low BIM adoption in SMOs were identified, which can explain 22% of the SMOs with a low BIM adoption level.

Table 13 Configurational Paths to Low BIM Adoption in SMOs

Configurations	SML1	SML2
TPU		⊗
TPE	⊗	
OTS		
OFC	⊗	
OBC		⊗
EGP	•	
ECP		•
Raw coverage	0.14	0.12
Unique coverage	0.03	0.02
Consistency	0.82	0.78
Solution coverage	0.22	
Solution consistency	0.84	

4.3 Research Findings

The following section reported these configurations presented above and identifies the complementary (Milgrom & Roberts, 1995), substitution, and suppression (Fiss, 2011) relationships among the conditions. To describe the configurations below, this study uses the symbol * to represent the logical operation AND and the symbol ~ to represent that the condition is absent or at a low level (at a low level, hereafter).

4.3.1 Configurations for High BIM Adoption in SMOs

It can be seen that four of the five configurations contain government pressure, which is the core condition for achieving high BIM adoption in SMH 1, 2, and 3, indicating that mandatory policy is a powerful enabler and is playing a critical role in promoting BIM adoption in the Hong Kong construction industry.

SMH1 (TPU*~OTS*OFC*~OBC*EGP*) shows a combination of organizational financial capacity, government pressure as core conditions, and perceived usefulness as the peripheral condition in a complementary way can lead to high BIM adoption rate when organizational top management support and organizational BIM capability are absent. This solution can explain 16% of the cases with a high BIM adoption rate.

SMH2 (TPU*~OTS*~OFC*OBC*EGP) indicates a combination of organizational BIM capability, government pressure as core conditions, and perceived usefulness as the peripheral condition in a complementary way can result in high BIM adoption rate when organizational top management support and organizational financial capacity are absent. Comparing SMH 1 and SMH 2, with perceived usefulness as the peripheral condition, government pressure as the core condition, and organizational top management support absent, there is a clear substitutability relationship between organizational financial capacity and organizational BIM capability. The second configuration can explain 16% of the cases with a high BIM adoption rate.

SMH 3 (TPU*~TPE*OTS*OFC*OBC*EGP) reflects a combination of organizational financial capacity and government pressure as the core conditions and perceived usefulness, organizational top management support, and organizational BIM capability as peripheral conditions in a complementary way can achieve a high BIM adoption rate in the absence of perceived ease of use. This configuration can explain 16% of cases with a high BIM adoption rate.

SMH 4 (TPE*OTS*OBC*EGP*ECP) shows a combination of competitor pressure as the core condition and perceived ease of use, organizational top management support, organizational BIM capability, and government pressure as the peripheral conditions in a complementary way can lead to high BIM adoption rate. This configuration can explain 15% of cases with a high BIM adoption rate.

SMH 5 (TPE*OTS*OFC*OBC*ECP) presents a combination of competitor pressure as the core condition and perceived ease of use, organizational top management support, organizational financial capacity, and organizational BIM capability as peripheral conditions in a complementary way can facilitate a high BIM adoption rate. Comparing SMH4 and SMH5, it can be found that there is a substitution relationship between government pressure and organizational financial capacity in the context of higher competitor pressure. This configuration can explain 22% of cases with a high BIM adoption rate.

4.3.2 Configurations for High BIM Adoption in LOs

Similar to BIM adoption in SMOs, in a sample of LOs, three of the four configurations contain government pressure, which is the core condition for leading high BIM adoption in LH2, LH3, and LH4, meaning that the main booster of BIM adoption in LOs is also mandatory policy.

LH1 (TPU*OTS*OFC) presents that a combination of perceived usefulness, organizational top management support as the core conditions, and organizational financial capacity as the peripheral condition in a complementary way can achieve high BIM adoption in LOs. Regarding the composition of this configuration, if top managers in organizations are fully aware of the potential benefits of using BIM in projects and are highly supportive of BIM adoption, the organizations will use BIM in most of their projects, supported by the organizations' financial capacity. These organizations usually have a high level of self-efficacy in BIM adoption and are leaders in the digital transformation in the Hong Kong construction industry. This configuration can explain 20% of cases with a high BIM adoption level.

LH2 (TPE*OTS*OBC*EGP) shows a combination of government pressure as the core condition and perceived ease of use, organizational top management support, and organizational BIM capability as the peripheral conditions in a complementary way that can lead to high BIM adoption in LOs. This configuration can explain 38% of cases with a high BIM adoption rate.

LH3 (OTS*OFC*OBC*EGP) displays that a combination of government pressure as the core condition and organizational top management support, organizational financial capacity, and organizational BIM capability as the peripheral conditions in a complementary way can result in a high BIM adoption rate in LOs. Compared with LH2, it is likely that a substitution relationship exists between perceived ease of use and organizational financial capacity under high government pressure. In LH3, organizational financial capacity replaces perceived ease of use, and together with organizational top management support, organizational BIM capability, and government pressure, it contributes to high BIM adoption rates in LOs. In other words, under high government pressure, organizations will invest financial resources to overcome difficulties in technology use and cater to policy requirements even if their perceived ease of use of BIM is lower. This configuration can explain 42% of cases with a high BIM adoption rate.

LH4 (TPU*TPE*OTS*EGP*ECP) indicates a combination of competitor pressure as the core condition and perceived usefulness, perceived ease of use, organizational top management support, and government pressure as the peripheral conditions in a complementary way pointing to high BIM adoption outcome in LOs. The path suggests that when high BIM adoption is market-driven, organizations are usually attracted by the advantages of the technology. Organizations adopt BIM to establish technological leadership advantages to improve or maintain market competitiveness. Meanwhile, it is essential to note that in LH4, government pressure is still working as a complementary condition, which indicates that the mandatory pressure promotes the marketization of BIM to a certain extent and, together with the competitor pressure, promotes the full adoption of BIM in the construction industry. This configuration can explain 24% of cases with a high BIM adoption rate.

4.3.3 Configurations for Low BIM Adoption in SMOs

As for the low BIM adoption, there are two configurations, SML1 (~TPE*~OFC*EGP) and SML2 (~TPU*~OBC*ECP). It is apparent from Table 12 that, in the absence of some technological conditions and organizational conditions, perceived ease of use and organizational financial capacity in SML1, and perceived usefulness and organizational BIM capability in SML2, the promotion effect of government pressure (see SML1) and competitor pressure (see SML2) on BIM adoption will fail to perform and exhibit policy failure or market failure to some degree. In SML1, the lack of perceived ease of use and organizational financial capacity offset the promotion effect of government pressure on BIM adoption, while in SML2, the absence of perceived usefulness and organizational BIM capability tends to suppress the positive effect of competitor pressure on BIM adoption. Overall, SML1 can explain 14% of cases with a low BIM adoption rate in SMOs, while SML2 explains 12% of cases with a low BIM adoption rate in SMOs.

4.3.4 Comparative Analysis of the Configurations in SMOs and LOs

Similarities of the configurations in SMOs and LOs

When looking at the similarities in the configurations, first, both in SMOs and LOs, there is no necessary condition to guarantee a high BIM adoption outcome, which is caused by the combination of technological, organizational, and environmental conditions. Moreover, government pressure in the form of mandatory policy is the dominant condition in bringing about a high BIM adoption both in LOs and SMOs. At the same time, the results of this study also indicate that, for LOs and SMOs, market-driven and government-driven paths coexist.

Differences in the configurations in SMOs and LOs

The differences in the configurations of SMOs and LOs exist in the following three aspects. In terms of the structure of configurations, the compositions of SMOs are relatively complex while simpler in LOs. Specifically, the four paths in LOs are pretty independent, as it is hard to identify the substitution or suppression relationships that exist among conditions, except for the substitution relationship between perceived ease of use and organizational financial capacity in LH2 and LH3, while in SMOs, substitution and suppression relationships between different conditions are more prevalent, as shown in Figure 8.

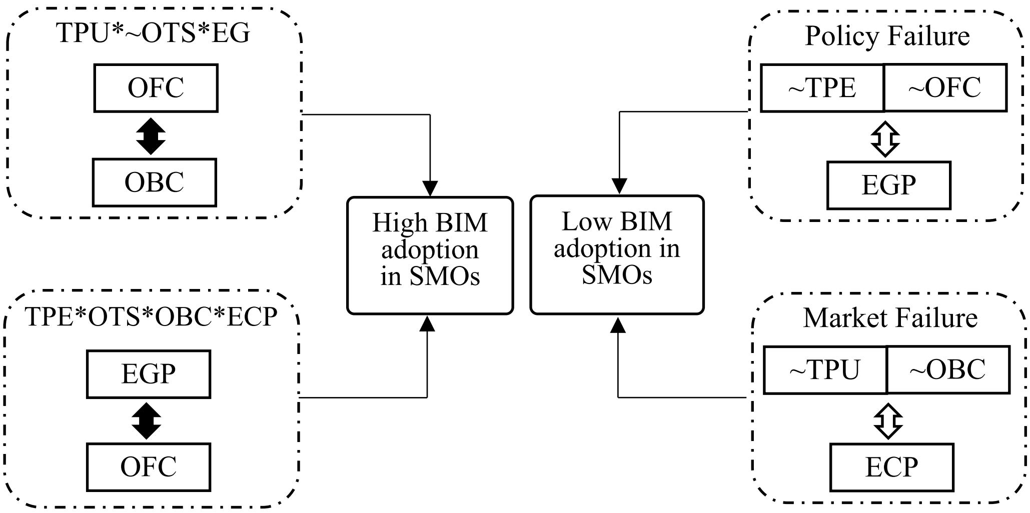

Figure 8 The Substitution and Suppression Relationships Between Conditions

Note: Solid arrows indicate substitution (on the left) and hollow arrows indicate suppression (on the right).

Furthermore, the core conditions in SMOs are dominated by the external environment, and BIM adoption is mainly promoted by external conditions; the potential for the collaborative domination of technological conditions and organizational conditions exists in LOs. As far as the three aspects of conditions are concerned, for SMOs, although there is still high BIM adoption when organizational conditions are absent (SMH1, SMH2, SMH4) or technological conditions are absent (SMH3), when both organizational and technological conditions are absent and performs as core conditions in the configurations (SML1, SML2), the BIM adoption of these SMOs is low. In this sense, in addition to the external environment, organizational conditions, especially organizational financial capacity, and organizational BIM capability, are still critical for SMOs to achieve high BIM adoption. Furthermore, for the LOs, an interesting finding is that organizational top management support emerges in all configurations, pointing to high BIM adoption. LOs can achieve a high BIM adoption rate with organizational top management support and perceived ease of use as core conditions and organizational financial capacity as the peripheral conditions. Regrettably, however, the presence of organizational top management support is not necessary for high BIM adoption, and the absence of organizational top management support is not necessary for low BIM adoption either. In contrast, LOs and SMOs are complementary in three organizational conditions, i.e., organizational BIM capability and financial capacity are more critical for BIM adoption in SMOs, because SMOs are always a constraint in these two aspects. While organizational top management support is more important for high BIM adoption in LOs, as the organizational structure and decision-making process of LOs are relatively complicated. At the same time, this means that the adoption of BIM in the LOS is more likely to face resistance from organizational structures and workflow, which is more flexible in SMOs.

Last but not least, the most prominent finding to emerge from this study is that there is no configuration leading to low BIM adoption in LOs. Although high BIM adoption is driven by the three dimensions of the "technology-organization-environment," there are no systemic explanations for low BIM adoption in LOs. The reasons for the low BIM adoption rate of LOs may be too dispersed to identify combinations of conditions with a powerful explanation.

5. Policy Implications and Recommendations

The application of innovative technologies such as BIM is the development trend in Hong Kong. However, based on the empirical analysis results of this study and the current situation of the Hong Kong construction industry, BIM application and implementation still face a series of problems and challenges. Given this, relevant policy suggestions are proposed from the following four aspects to effectively facilitate the diffusion of BIM in the regional construction industry and, in turn, promote the market competitiveness of the Hong Kong construction industry in the application of related innovative technologies.

5.1 Formulating Policy Portfolios to Enhance the Adaptability of BIM Policies to the Multiplicity of Institutions in the Regional Construction Industry

According to the above analysis result, the current BIM policies have a low coverage for small and medium-sized organizations. To be specific, QCA analysis results show that the combinations of conditions that promote BIM adoption in LOs and SMOs exists significant differences. This research elaborated five configurations pointing to high BIM adoption and two configurations pointing to low BIM adoption in the sample of 36 SMOs, and four configurations pointing to high BIM adoption and no path leading to low BIM adoption in the sample of 38 LOs. At the same time, as visualized in Figure

9, the gap in BIM adoption rates between LOs and SMOs is growing year by year. In addition, the results of the PSM-DID heterogeneity analysis indicated that compared with SMOs, the LOs are more likely to realize more benefits by adopting BIM in their projects. These results indicate that although the mandatory policy directly promotes the adoption of BIM in the construction industry, the performance of SMOs in applying BIM projects has not been significantly improved compared to LOs' mature BIM application practices. The organization's BIM capabilities and position in BIM-based collaborative network projects remain peripheral and have not benefitted well from the policy. Given the critical role of SMOs in contributing to the Hong Kong construction industry, future policies should be appropriately tilted towards SMOs, supplementing the current policy framework with more precise support initiatives to facilitate the application of BIM throughout the regional construction industry.

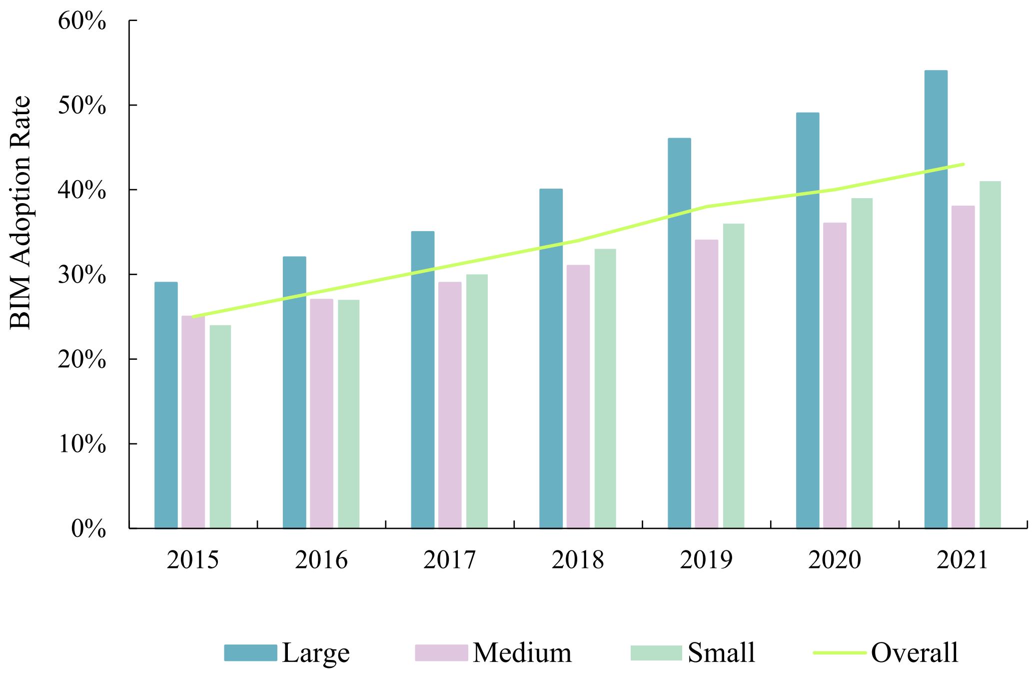

Figure 9 Evolution of BIM Adoption Rate Distribution by Organization Size

Therefore, to eliminate the “digital divide” in BIM adoption practices between LOs and SMOs in the regional construction industry, government agencies are suggested to shift the focus of policy formulation from projects to organizations and develop more specific support and incentive policies based on the organizational characteristics of SMOs to help them better benefit from BIM adoption. An essential aspect of these measures is setting up policy portfolios based on the five configurations identified in this study to meet SMOs’ diversified needs and help them improve their project performance. At the same time, the effectiveness of the policy can be significantly enhanced by pairing it with a series of pilot programs, from point to surface, promoting it in the industry based on the policy outcome and performance of the pilot organization.

5.2 Formulating Learning Strategies and Establishing Communication Platforms to Promote the Further Diffusion and Implementation of BIM in Hong Kong

The analysis result also provides clear evidence that organizational learning and knowledge management are critical steps to promote the successful implementation of BIM both in SMOs and LOs. In detail, regarding SMOs, in the configurations with perceived usefulness as the peripheral condition, government pressure as the core condition, and organizational top management support absent, there is a clear substitutability relationship between organizational financial capacity and organizational BIM capability. Hence, SMOs can compensate for their weaknesses in financial capability through enhanced learning and effective knowledge management. At the same time, the absence of BIM capability is found to be the core condition leading to low BIM adoption according to one of the configurations. More importantly, organizational BIM capability exists as core or peripheral conditions in four of five configurations that result in high BIM adoption. Meanwhile, concerning LOs, organizational top management support seems more vital for them to implement BIM within an organization as this condition is included in all five configurations that result in high BIM adoption, a plausible explanation for this result is that the organization structure of LOs is more complex, which makes it necessary to spend a lot of time on organization structure and operation process changes.

As such, although some relevant bodies like the Hong Kong Institute of Building Information Modelling (HKIBIM) and Construction Industry Council (CIC) have made some efforts to improve their member organizations' BIM skills and knowledge, including regular BIM workshops, seminars, and technical forums, there is still a need for a long-term plan for the industry to learn BIM-related knowledge in the future. In detail, government agencies are suggested to provide more training opportunities, proactively open courses and activities on advanced building innovations, and set more targeted and instructive training programs to better provide technical support. At the same time, the government can also guide enterprises to establish learning organizations, and direct team members to carry out internal knowledge exchanges to achieve effective transformation of training results. In addition, this study advocates the government to invest more in the training of BIM talents, or encourage organizations to establish a long-term partnership with local universities to provide professional and technical talent for the construction industry.

5.3 Introducing Diversified Supportive Initiatives to Mitigate the Uneven Trend among Different Organizations in BIM Application

In general, the implementation of mandatory policies improved the performance of companies' BIM-based projects in terms of subjective BIM performance and BIM ROI. As shown in Figures 10-13, the annual average BIM ROI (Figures 10 and 11) and annual average BIM subjective performance (Figures 12 and 13) show an increasing tendency during 2015-2021. However, the impact of the mandatory policy presents apparent heterogeneity across the three types of organizations. Empirical results show that, regarding the types of organizations, the policy has the strongest impact on the owners' BIM performance, followed is the contractors. However, the promotion effect on the design consultants is not significant.

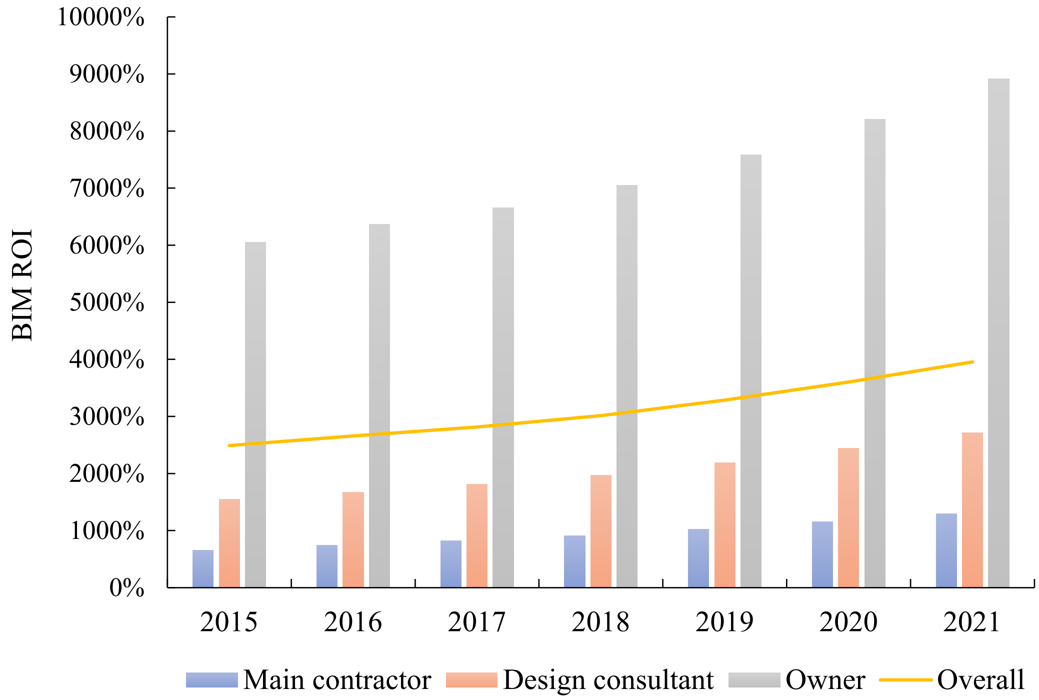

Figure 10 Evolution of BIM ROI Distribution by Organization Role

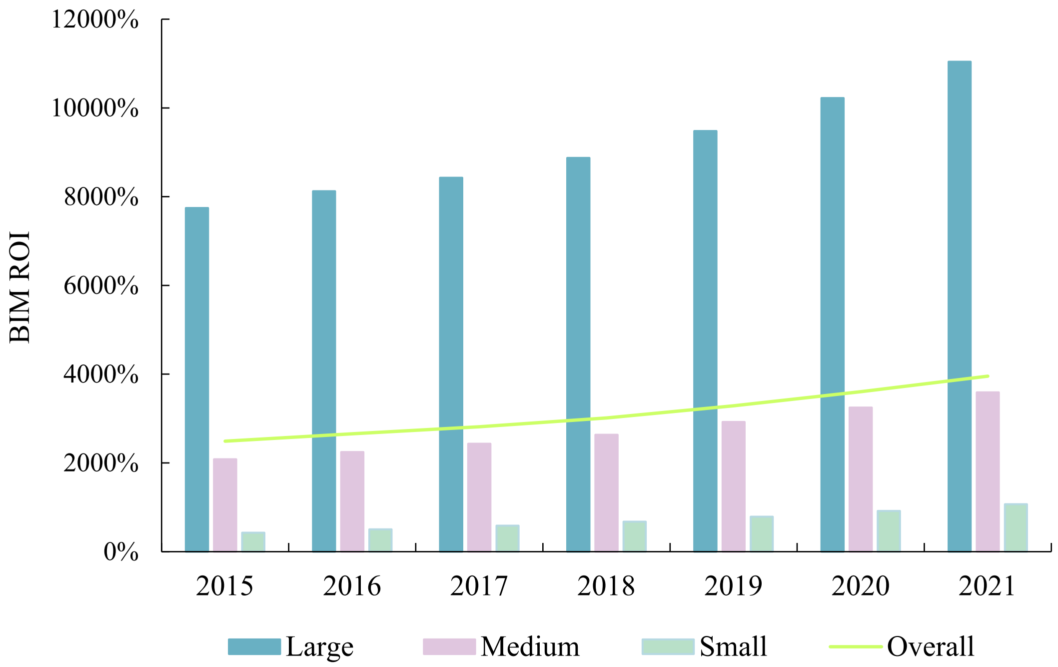

Figure 11 Evolution of BIM ROI Distribution by Organization Size

The above results are also evident from the magnitude of changes in the bars representing the three stakeholders in Figure 11 and Figure 13. Concerning organizations of different sizes, the results indicate that the policy has a positive impact on large-size organizations and medium-sized organizations but a limited impact on small organizations. The changing magnitude in the bars in Figure 11 and Figure 13 has also provided explanations for the differences in the BIM-based project performance of organizations of different sizes. Both the objective assessment of BIM benefits and subjective perception will strongly influence the organizations' BIM adoption behavior in the future. The above trends on the divergent performance of BIM among different organizations might exacerbate the uneven trend of BIM application in the construction industry and hinder the deep diffusion of BIM in Hong Kong.

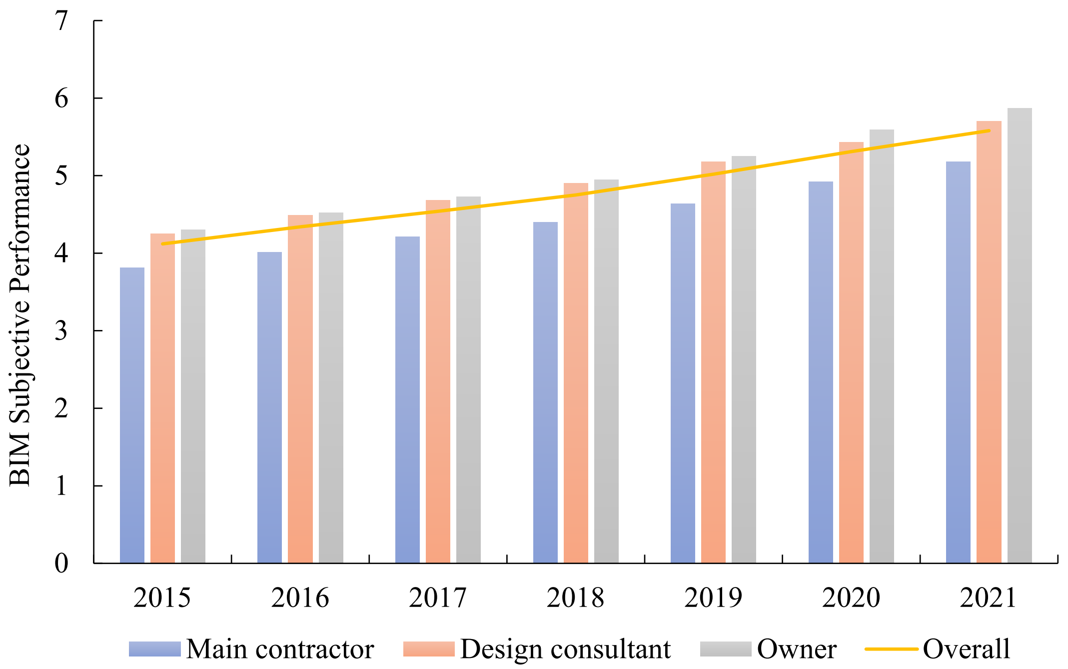

Figure 12 Evolution of BIM Subjective Performance Distribution by Organization Role

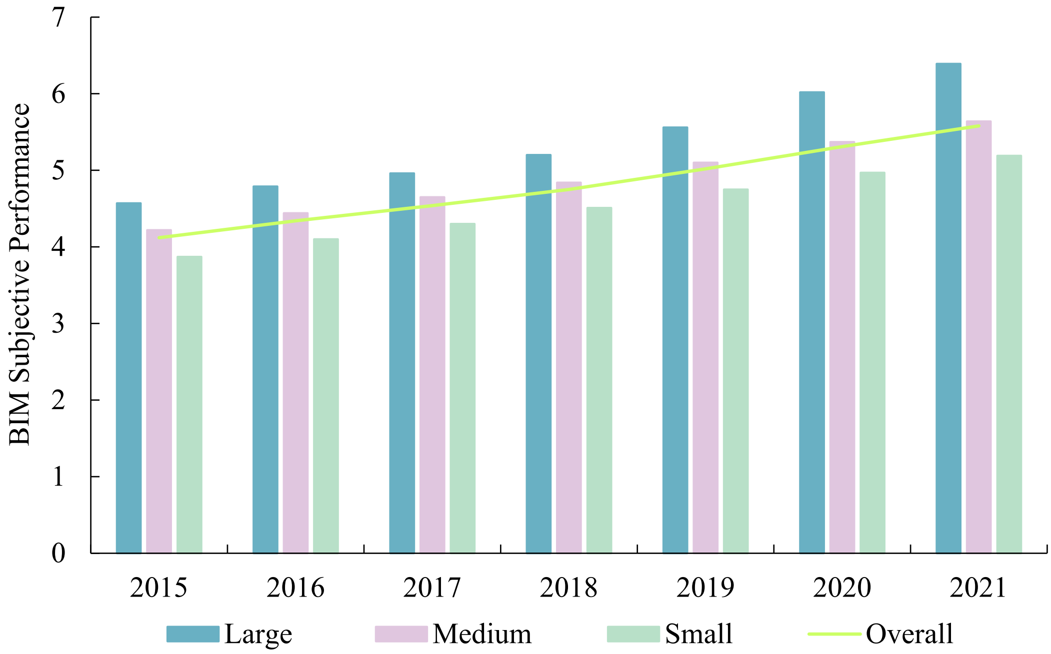

Figure 13 Evolution of BIM Subjective Performance Distribution by Organization Size

Therefore, it is necessary to introduce some diversified supportive initiatives to mitigate the negative effect of the uneven trend to increase the interest of participating parties in adopting BIM and further increase the prevalence of the positive outcome of mandatory policies. To be specific, for inter-organization communication, on the one hand, the government can establish a BIM communication platform and regularly invite companies with mature BIM application practices to share their experiences. Effective communication is the key to improving the positive results of innovative technology applications, it will also help to strengthen the knowledge of BIM for companies that are relatively lagging at the present stage. At the same time, companies with well-performing BIM-based projects can be showcased as industry benchmarks to strengthen the organization's perception of the economic and social benefits of BIM implementation. On the other hand, the government is also suggested to consider holding regular BIM-related knowledge and technology competitions to promote communication and technology learning among different companies and thus reinforce their understanding of BIM applications. Specifically, the government can qualify organizations for BIM technology based on the results of the competition. Meanwhile, to promote effective collaboration among organizations, the government can encourage SMOs to establish BIM alliances on their initiative. The government can also try to introduce joint bidding projects in some specific public projects to provide SMOs with more opportunities for conversion and application of learning achievements. Thus to further promote the proliferation of BIM-related knowledge in the Hong Kong construction industry.

5.4 Establishing a Comprehensive Evaluation System to Ensure the Effectiveness of BIM-Related Policies

Since this study is the first attempt to examine the impact of policy interventions on BIM-based project performance in Hong Kong, the results of the study can also provide a basis for future innovative-related policy formulation. The results of this study indicate that the impact of BIM mandatory policy shows obvious heterogeneity among different stakeholders and organizations of different sizes. In detail, design consultants and small organizations are not well-positioned to benefit from the positive effects of mandatory BIM policy implementation. The effectiveness of the policy still needs to be strengthened. Therefore, based on this, this study suggests that in the process of formulation of BIM-related policies, it is necessary to establish a set of corresponding policy evaluation systems and develop evaluation indicators based on policy objectives and establish a long-term tracking mechanism to gain a comprehensive understanding of the impact produced by policy interventions and thus enhance the effectiveness of policies. In detail, the government and its affiliated organizations are suggested to conduct regular investigations and collect feedback from the industry in phases during the policy implementation process, to record and summarize the issues related to the implementation of the policy at different stages. It is also advisable to invite industry professionals to share their insights by organizing seminars and other activities after the policy has been implemented for a period of time.

6. Conclusions and Effectiveness of the Research Project

6.1. Conclusions

This research aims to provide a systemic summary of BIM initiatives taken by the public sector and examine how the public policy impacted the BIM adoption and implementation practices in the Hong Kong construction industry. Based on the data analysis results of PSM-DID analysis and case study, the research team has successfully assessed the impacts of the first BIM mandatory policy issued by the Hong Kong government. The analysis result reveals that the policy has achieved greater BIM diffusion in the regional construction industry, However, the implementation of the policy was accompanied by some unintended consequences. The major findings of this research are as follows.

1) Based on the analysis result of PSM-DID research on the panel data from 2015-2020 of 584 organizations, this study has successfully investigated the impact of the first mandatory policy on the BIM-based project performance of three major types of organizations in the construction industry. The implementation of the mandatory policy has significantly improved the performance of the BIM-based project in terms of subjective BIM performance and BIM ROI, providing substantial support for the development of the construction industry in the region. From a temporal perspective,

the promotion effect of the mandatory policy on BIM-based project performance gradually increases year by year and exhibits a clear dynamicity. Both subjective BIM performance and BIM ROI of the treated group show a gradually increasing trend in the investigated period.

2) The analysis result of PSM-DID also reveals that, from a heterogeneous perspective, the impact of the mandatory policy shows significant heterogeneity across the three kinds of organizations and organizations of different sizes. On one hand, the policy has a significant impact on owners' BIM performance, with contractors second. However, the promotion effect on the design consultants is not significant. Regarding the organization size, the policy also shows a positive impact on large-size organizations and medium-sized organizations. However, it has limited effect on enhancing the practice of BIM application for small organizations.

3) This research also explored the promotion mechanism of BIM adoption in the Hong Kong construction industry from a configuration perspective according to the result of the quantitive analysis of 74 organizations. The analysis result reveals that there is no necessary condition to result in a high or low BIM adoption rate caused by the combination of technological, organizational, and environmental conditions. Specifically, five configurations led to high BIM adoption in SMOs, four

configurations led to high BIM adoption in LOs, and two configurations resulted in low BIM adoption in SMOs has been found.

4) The analysis results also provide evidence that government pressure in the form of mandatory policies plays a dominant role in generating high BIM adoption rates. And when competitor pressure is complemented by technical and organizational conditions, BIM adoption can be promoted in certain circumstances. Overall, the adoption of BIM in SMOs and LOs is primarily driven by the external environment, where government-driven and market-driven forces co-exist.

Based on these above empirical findings, the following four aspects of policy suggestions are specifically proposed to facilitate the development of BIM in Hong Kong: 1) Formulating policy portfolios to enhance the adaptability of BIM policies to the multiplicity of institutions in the regional construction industry; 2) Formulating learning strategies and establishing communication platforms to promote the further diffusion and implementation of BIM in Hong Kong; 3) Introducing diversified supportive initiatives to mitigate the uneven trend among different organizations in BIM application; 4) Establishing a comprehensive evaluation system to ensure the effectiveness of BIM-related policies

6.2. Effectiveness of the Research Project

Table 14 summarized the research objectives achieved in this research project. The three originally proposed objectives have been satisfactorily achieved.

Table 14 Summary of the Objectives Achieved in this Research Project

Code	Proposed objectives	Achievements
Objective 1	To investigate and summarize the relevant BIM initiatives taken by the public sector in the Hong Kong construction industry	Achieved. The research findings have summarized and illustrated the relevant BIM initiatives in Section 2.1.
Objective 2	To illustrate and compare BIM adoption behavior among organizations in the Hong Kong construction industry before and after the implementation of the mandatory policy.	Achieved. The research findings on the impacts of relationship networks on organizational BIM implementation practices of design consultants and main contractors are presented in Section 4.3.
Objective 3	To recommend strategies to facilitate the diffusion of BIM among organizations in Hong Kong based on the propensity score matching difference-in-difference analysis and qualitative comparative analysis results.	Achieved. As shown in Section 5, a total of four aspects of strategies have been proposed.

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Details of the Public Dissemination

The results of the research obtained in this project are summarized in three papers, which have been submitted for review. The details of the three papers are listed in Table 15. Meanwhile, the research team has attended an international symposium to share the findings of this project with academia and industry.

Symposium: Multiculturism and Multimodality in Architecture:1st AKAN Symposium
Date: 25 August 2022
Venue (Hybrid): Room No. 707 at Advanced Materials & Chemical Engineering Building, Hanyang Univ.
Presentation Title: Dynamic evolution of collaboration network on BIM-based projects in Hong Kong

Table 15 Research Outputs

List of Journal Paper		
No.	**Title**	**Name of Journal**
1.	Exploring the impact of policy interventions on project performance through a PSM-DID approach: Evidence from the Hong Kong construction industry	Engineering, Construction, and Architectural Management (under review)
2.	Investigating the adoption of Building Information Modelling of small-medium sized organizations in the Hong Kong construction industry from a configuration perspective	Journal of Building Engineering (under review)
3.	System dynamics model based on dynamic evolutionary game theory for the behavior of BIM implementation among construction stakeholders: Case in Hong Kong	Journal of Management in Engineering (under review)
List of Symposium		
The symposium detail can be found through the following link, and the poster of the conference has been attached in Appendix C https://auskorarch.net/symposium/		

Appendices

Appendix A. Questionnaire Suvery_Part I

THE HONG KONG POLYTECHNIC UNIVERSITY
香港理工大學

Survey on Policy Interventions on the BIM Adoption Status in Hong Kong

Dear Sir or Madam,

As a milestone technology to parametrically model and integrative manage project lifecycle information, Building Information Modeling (BIM) has drawn increasing interest from construction practitioners over the past decade. Aware of the tremendous revolution that BIM has brought to the traditional construction industry, the Hong Kong Government issued the first mandatory policy on adopting BIM for Capital Works Projects in 2018. Financially supported by the Public Policy Research Funding Scheme from the Hong Kong government (Grant No. 2021.A6.173.21B), this investigation aims to evaluate the policy interventions on the BIM adoption status in Hong Kong. Given your expertise and experience related to BIM, you are cordially invited to spare your precious time to participate in our questionnaire survey.

Please answer the questions based on the information of BIM-based projects in your company/organization, and all the answers should be based on the situations in Hong Kong. It will take you about 10~20 minutes to complete the questionnaire. All collected data will be used only for academic purposes, and the information related to specific projects and respondents will be strictly confidential. It would be appreciated if you could return the answer sheet directly to this Email (**krystal.li@polyu.edu.hk**). If you are interested in the research results, we will send you an electronic copy of the research report upon the accomplishment of this research. We greatly appreciate your support for our research!

Yours sincerely,

Heng Li, Chair Professor

Tel: (852) 2766 5803 Fax: (852) 2364 9322

Email: heng.li@polyu.edu.hk

Smart Construction Laboratory, ZN1002, Block Z

The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

Part I: *Basic Information about* Organizational Characteristics

1. Role of your company/organization: (   )

   A. Main contractor   B. Designer   C. Client

2. Approximate number of full-time employees in your company/organization **yearly**:

Year	2015	2016	2017	2018	2019	2020	2021
Number							

3. Ownership type of your company/organization: (   )

   A. Multi-national Company   B. Local Company

4. The year around which BIM was **firstly used** in your company/organization: ___________

5. Approximate percentage of projects in your company/organization using BIM **yearly**:

Year	2015	2016	2017	2018	2019	2020	2021
%							

6. The establishment year of your company: ___________

Part II: *Organizational Capability Relating to BIM Implementation*

Justification: Please indicate how BIM was implemented in your company/organization according to the list areas. The extent to which you agree with the listed statements regarding **the BIM implementation practice in your company/organization**, you can use "√ " to mark your response.

If you have implemented the BIM functions, please select **"Y" (for Yes)** and then specify **the status of your implementation practice yearly**, **"0" (not use), "1" (some use), and "2" (extensive use).**

If you haven't implemented the function, you can select **"N" (for No) and directly move to the next option**. [For more detailed explanations of the lasted are, please refer to "*CIC BIM Standards - General (Version 2.1 - 2021)*]

BIM Implementation Areas																					**Practice**
【You could use "√" to mark your response.】																				Y	N
Design Phase																					
01	***Design Authoring***: Utilize BIM software to design and three-dimensionally (3D) represent different building systems of the project																				
Year	**2015**			**2016**			**2017**			**2018**			**2019**			**2020**			**2021**		
Status	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2
Response																					
02	***Design Reviews***: Related stakeholders review BIM models to provide feedback and to validate related details of the proposed design																				
Year	**2015**			**2016**			**2017**			**2018**			**2019**			**2020**			**2021**		
Status	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2
Response																					
03	***Drawing Generation (Drawing Production)***: Utilize BIM software to prepare plan view and elevation view for statutory submission, tender drawings, construction, and shop drawings																				
Year	**2015**			**2016**			**2017**			**2018**			**2019**			**2020**			**2021**		
Status	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2
Response																					
04	***Existing Conditions Modelling***: Develop a 3D model of the existing site conditions with the help of laser scanning or conventional survey methods																				
Year	**2015**			**2016**			**2017**			**2018**			**2019**			**2020**			**2021**		
Status	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2
Response																					
05	***Site Analysis in the Design Phase***: Utilize BIM/GIS tools to evaluate properties in a given area to determine the most optimal site location for the future project																				
Year	**2015**			**2016**			**2017**			**2018**			**2019**			**2020**			**2021**		
Status	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2
Response																					
06	***Spatial Coordination in the Analysis Phase:*** Utilize BIM software to eliminate design errors before the construction of the project, such as checks for spatial and headroom requirements, working spaces for building operations, and maintenance activities																				
Year	**2015**			**2016**			**2017**			**2018**			**2019**			**2020**			**2021**		
Status	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2
Response																					

07 ***Engineering Analysis***: Utilize BIM software to assist, analyze and optimize different design options to determine the most effective engineering

Year	2015			2016			2017			2018			2019			2020			2021		
Status	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2
Response																					

08 ***Facility Energy Analysis***: Utilize BIM software to conduct energy assessments of a project design to optimize the design to reduce energy costs hence life cycle

Year	2015			2016			2017			2018			2019			2020			2021		
Status	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2
Response																					

Construction Phase

01 ***Phase Planning (4D Modelling)***: Develop 4D models based on schedule information to visualize and analyze the sequence of construction activities

Year	2015			2016			2017			2018			2019			2020			2021		
Status	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2
Response																					

02 ***Digital Fabrication***: Digitalising the construction details in the Information Model

Year	2015			2016			2017			2018			2019			2020			2021		
Status	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2
Response																					

03 ***3D Control and Planning***: Utilize BIM models to layout project elements, such as the position and depth of elements

Year	2015			2016			2017			2018			2019			2020			2021		
Status	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2
Response																					

04 ***Construction System Design***: Utilize BIM models to design and analyze the supplementary construction systems to optimize the planning and construction process

Year	2015			2016			2017			2018			2019			2020			2021		
Status	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2
Response																					

05 ***Construction Quality Management***: Utilize a Construction Quality Management system (CQMS) during the construction stage to support viewing and navigating of Information Models

Year	2015			2016			2017			2018			2019			2020			2021		
Status	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2
Response																					

06 ***As-Built Modelling and Asset Information Modelling***: Create a post-construction record model to accurately represent the physical conditions, environment, and assets of the constructed facility

Year	2015			2016			2017			2018			2019			2020			2021		
Status	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2

Response																					
07	***Site Utilisation Planning***: Utilize BIM models to graphically represent permanent and temporary on-site facilities to plan effective utilizations of the construction site																				
Year	**2015**			**2016**			**2017**			**2018**			**2019**			**2020**			**2021**		
Status	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2
Response																					
<u>Design or Construction Phase</u>																					
01	***3D Construction Coordination***: Utilize the BIM software to further coordinate the federated Information Models from the design stage to the construction stage																				
Year	**2015**			**2016**			**2017**			**2018**			**2019**			**2020**			**2021**		
Status	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2
Response																					
02	***Existing Conditions*** Modelling: Utilize the BIM software to create a 3D model																				
Year	**2015**			**2016**			**2017**			**2018**			**2019**			**2020**			**2021**		
Status	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2
Response																					
03	***Building Code Checking and Validation***: Utilize the BIM software to review compliance with building codes and regulations that apply to the project through one or more Information Models.																				
Year	**2015**			**2016**			**2017**			**2018**			**2019**			**2020**			**2021**		
Status	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2
Response																					
04	***Cost Estimation***: Utilize BIM models to generate accurate quantity take-off and cost estimating in the design phase, and 5D modeling/cash flow forecasting in the construction phase																				
Year	**2015**			**2016**			**2017**			**2018**			**2019**			**2020**			**2021**		
Status	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2
Response																					
05	***Sustainability Evaluation***: Utilize the BIM software to evaluate the project model based on BEAM Plus, LEED, or other sustainable/green building criteria																				
Year	**2015**			**2016**			**2017**			**2018**			**2019**			**2020**			**2021**		
Status	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2
Response																					

Part III: Organizational Performance Impacts Relating to BIM Implementation

Justification: **Please refer to the <u>BIM-based public projects or BIM-based private projects respectively</u> in your company/organization**, and indicate the extent to which you agree with the listed statements regarding **the overall impact of BIM implementation on these two kinds of projects "yearly".**

1. **<u>Communicatie Performance</u>:** Please indicate the extent to which you agree that the BIM has improved the effectiveness of the design/construction information exchanged among project participating organizations:

A. Strongly Disagree B. Disagree C. Slightly Disagree D. Neutral

E. Slightly Agree F. Agree G. Strongly Agree

Project/Year	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Public							
Private							

2. **<u>Cost Overrun</u>**: Please indicate the level of the actual construction cost as compared with the original construction contract value in this project:

A. Increased more than 20% B. Increased 11–20% C. Increased 1–10%

D. Stayed the same E. Decreased 1–10% F. Decreased 11–20%

G. Decreased more than 20%

<u>* If possible, please give a specific number after the options,e.g., C (7%)</u>

Project/Year	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Public							
Private							

3. **<u>Schedule Overrun</u>**: Please indicate the actual construction duration as compared with the planned construction duration (as specified in the construction contract) in this project:

A. Increased more than 20% B. Increased 11–20% C. Increased 1–10%

D. Stayed the same E. Decreased 1–10% F. Decreased 11–20%

G. Decreased more than 20%

**** If possible, please give a specific number after the options,e.g., E (-7%)***

Project/Year	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Public							
Private							

4. **Quality Performance**: Please indicate the extent to which the overall quality of the final delivered facility has met the client's expectations in this project:

A. Significantly below expectations B. Slightly below expectations C. Meeting expectations D. Slightly exceeding expectations E. Significantly exceeding expectations

Project/Year	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Public							
Private							

5. **Return of Investment (ROI)**: Please fill the table with the approximate benefits and investments relating to **BIM-based public projects or BIM-based private projects respectively** in your company.

Year / Project		**Benefits from BIM-based projects (*Public or Private*)**	**Investment on BIM**	
			Purchase Software/Hardware	***Staff Training***
2015	Public			
	Private			
2016	Public			
	Private			
2017	Public			
	Private			
2018	Public			
	Private			
2019	Public			
	Private			
2020	Public			

	Private			
2021	Public			
	Private			

End of the questionnaire.

Thanks a lot for your support for our research!

If you are interested in the research results, please write down your email address, and we will send you an electronic copy of the research report upon the accomplishment of this research. You could also write down your suggestions on our research here:

____

____

Appendix B. Questionnaire Suvery_Part II

THE HONG KONG POLYTECHNIC UNIVERSITY
香港理工大學

Survey on Factors Influencing BIM Adoption in Hong Kong

Dear Sir or Madam,

As a milestone technology to parametrically model and integrative manage project lifecycle information, Building Information Modeling (BIM) has drawn increasing interest from construction practitioners over the past decade. Aware of the tremendous revolution that BIM has brought to the traditional construction industry, the Hong Kong Government issued the first mandatory policy on adopting BIM for Capital Works Projects in 2018. Financially supported by the Public Policy Research Funding Scheme from the Hong Kong government (Grant No. 2021.A6.173.21B), this investigation aims to examine the effective combinations of conditions leading to high or low BIM adoption rates in SMOs and LOs in the Hong Kong construction industry. Given your expertise and experience related to BIM, you are cordially invited to spare your precious time to participate in our questionnaire survey.

Please answer the questions based on the information of BIM-based projects in your company/organization, and all the answers should be based on the situations in Hong Kong. It will take you about 10 minutes to complete the questionnaire. All of the collected data will be used only for academic purposes, and the information related to specific projects and respondents will **be kept in strict confidence**. If you are interested in the research results, we will send you an electronic copy of the research report upon the accomplishment of this research. We greatly appreciate your support for our research!

Yours sincerely,

Heng Li, Chair Professor

Tel: (852) 2766 5803 Fax: (852) 2364 9322

E-mail: heng.li@polyu.edu.hk

Smart Construction Laboratory, ZN1002, Block Z

The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

Part I: *Basic Information about* Organizational Characteristics

1. Role of your company/organization: (   )

   A. Main contractor   B. Designer consultant   C. Owner

2. Approximate number of full-time employees in your company/organization: (   )

   A. Less than 250   B. 250 or more

3. Ownership type of your company/organization: (   )

   A. Multi-national Company   B. Local Company

4. The establishment year of your company/organization: ____________

5. Approximate percentage of projects in your company/organization using BIM: ___________

Part II: Factors *Relating to BIM Adoption*

Please indicate **the extent to which you agree with the listed statements** using the following scale:

A	B	C	D	E	F	G
Strongly disagree	**Disagree**	**Disagree lightly**	**Neutral**	**Slightly agree**	**Agree**	**Strongly agree**

Technological Factors Relating to BIM Adoption							
You could **use any symbol (such as "√") to mark your response.**	**Disagree > Agree**						
	A	**B**	**C**	**D**	**E**	**F**	**G**
1. We adopted BIM because it always performs well in improving scheduling.							
2. We adopted BIM because it always performs well in controlling cost							
3. We adopted BIM because it always performs well in enhancing collaboration							

4. We adopted BIM because it always performs well in improving quality							
5. It is easy for us to learn and be on top of BIM.							
6. BIM is easy and skillful to use to handle work tasks							
7. In general, it is easy to use BIM							
Organizational Factors Relating to BIM Adoption							
You could **use any symbol (such as "√") to mark your response**.	**Disagree**			**>**			**Agree**
	A	**B**	**C**	**D**	**E**	**F**	**G**
1. Top managers of our company always provide a supportive climate and resources for the adoption of BIM							
2. Top managers of our company are highly interested in adopting BIM.							
3. Our company has sufficient funding for purchasing BIM-related equipment and software							
4. Our company has sufficient funding for training BIM employees.							
5. Our team is experienced in implementing BIM							
6. Our team is capable of solving the possible technical problems of BIM							
7. Our team is equipped with the knowledge necessary for implementing BIM							
8. Our team is familiar with the benefits of BIM tools.							
Environmental Factors Relating to BIM Adoption							
You could **use any symbol (such as "√") to mark your response**.	**Disagree**			**>**			**Agree**
	A	**B**	**C**	**D**	**E**	**F**	**G**
1. The decision to adopt BIM in our company was influenced by the mandatory policies from the government							
2. In the face of the BIM adoption decision, mandatory policies from the government put a lot of pressure on us							

3. Whether competitors have adopted BIM influences the decision to adopt BIM in our firm							
4. In the face of the BIM adoption decision, competitors' BIM adoption behaviors put a lot of pressure on us							

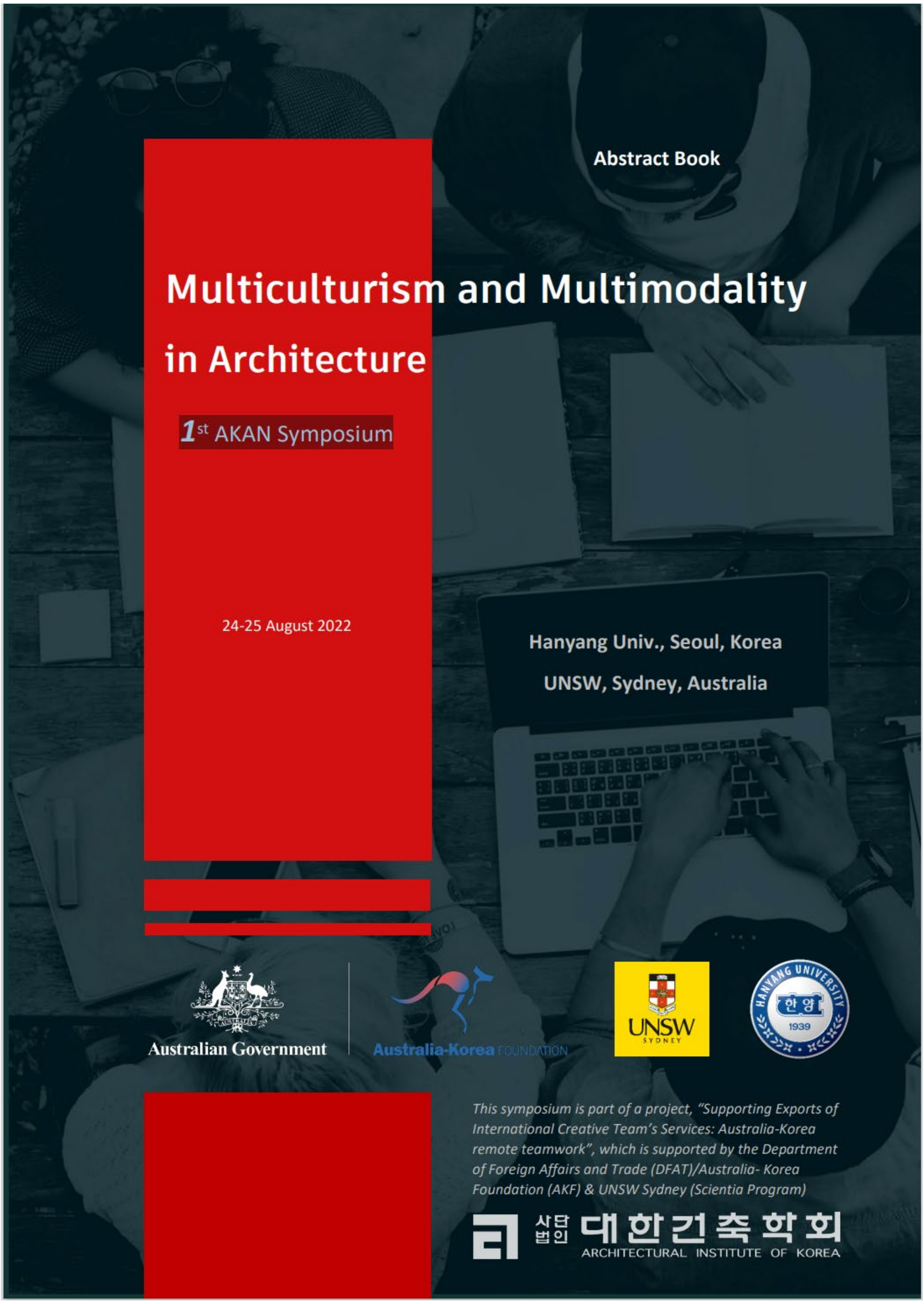
End of the questionnaire.

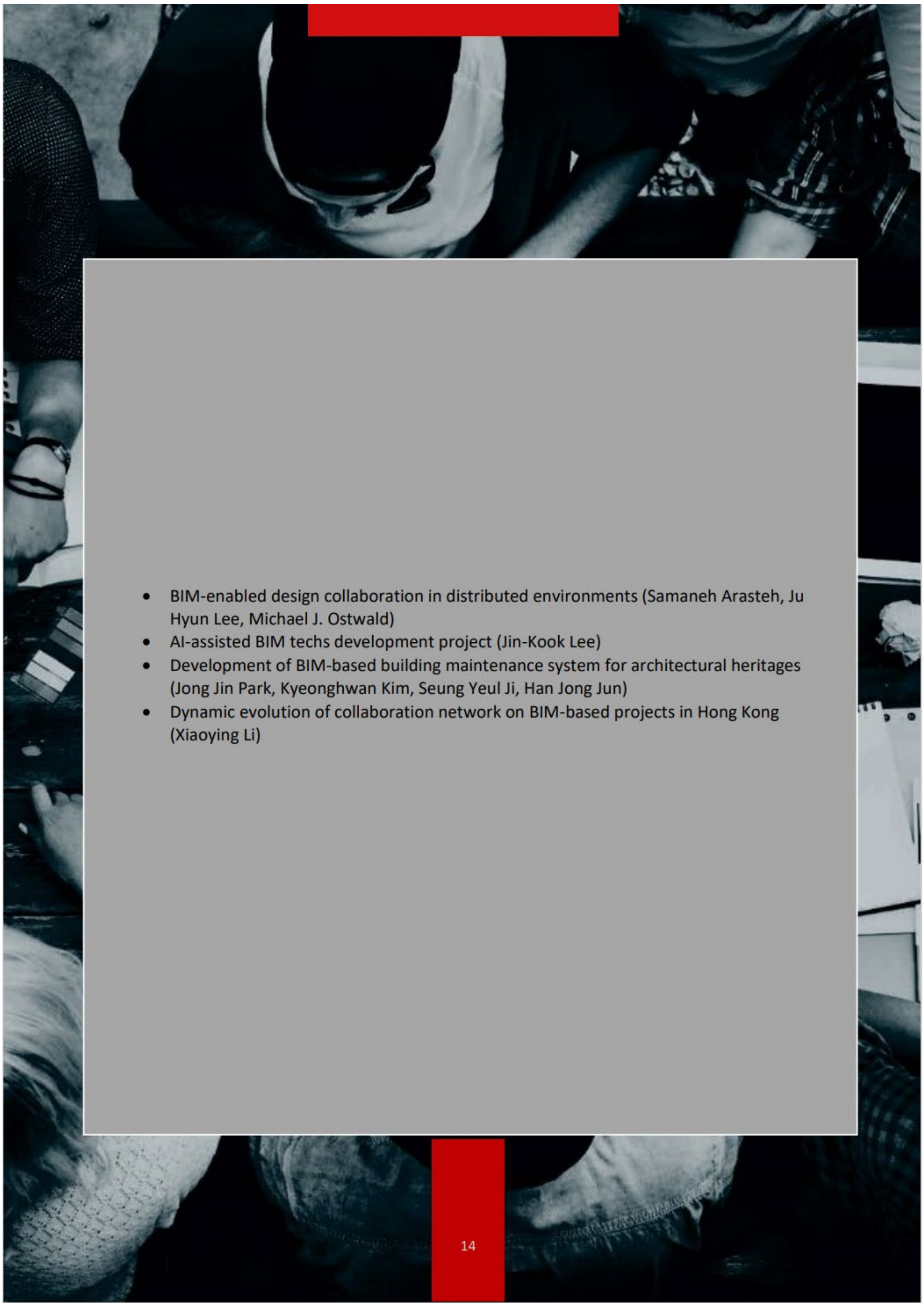
Thanks a lot for your support for our research!

If you are interested in the research results, please write down your email address, we will send you an electronic copy of the research report upon the accomplishment of this research. You could also write down your suggestions on our research here:

____

Appendix C. Snapshots of Symposium Information





- BIM-enabled design collaboration in distributed environments (Samaneh Arasteh, Ju Hyun Lee, Michael J. Ostwald)
- AI-assisted BIM techs development project (Jin-Kook Lee)
- Development of BIM-based building maintenance system for architectural heritages (Jong Jin Park, Kyeonghwan Kim, Seung Yeul Ji, Han Jong Jun)
- Dynamic evolution of collaboration network on BIM-based projects in Hong Kong (Xiaoying Li)

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