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Invigorating Modular integrated Construction Uptake in Hong Kong: A System Dynamics Model for Simulating Policy-Driving Forces

Abstract

Purpose - This study examines the Policy-Driving Forces (PDFs) influencing the adoption of Modular Integrated Construction (MiC) in Hong Kong (HK). It focuses on understanding how these forces impact MiC implementation across different construction phases, providing insights for policymakers to enhance sector productivity, efficiency, and sustainability.

Design/methodology/approach - Utilizing system dynamics (SD) modeling, this research simulates the dynamic influence of PDFs on MiC adoption throughout various construction stages. Data collection involved questionnaires, surveys, and case studies, which established the basis for detailed simulation scenarios to understand the timing and impact of PDFs.

Findings – The results indicate that PDFs exert the most significant influence during the initiation phase of MiC adoption, followed by the construction and planning/design phases. Regulative PDFs emerged as the most potent drivers in enhancing MiC uptake at each phase. Based on these insights, the study proposes six strategic recommendations to promote MiC adoption, emphasizing the utility of MiC in emergency infrastructures.

Originality - This research introduces a novel application of SD modeling to quantitatively assess the impact of PDFs on MiC adoption in Hong Kong's construction

industry. It provides a dynamic, systematic perspective on policy impacts, offering actionable insights for effective policymaking. Through scenario simulations, this study equips policymakers with the tools to foresee outcomes of policy adjustments, thus enabling informed decisions to foster widespread MiC adoption for sustainable development.

Keywords: Modular integrated Construction (MiC); System Dynamics (SD); Policy-Driving Forces (PDFs); Hong Kong

1. Introduction

Modular integrated Construction (MiC) is an emerging innovative construction method (Thompson 2019; Xu et al. 2020). The most constructive components are manufactured remotely in the offsite factory, and then assembled into a module before transporting by specific vehicles to the construction site for further building (Iacovidou et al. 2021). The MiC approach has several intrinsic advantages if appropriately managed, such as the reduction in waste generation (Pan and Zhang 2023; Pervez et al. 2021), onsite construction time (Li et al. 2021), decrease in manpower required during assembly (Xu et al. 2020), and improvements in quality, safety, and sustainability (Jin et al. 2022). Thus, it is significant to maximise the positive influence of adopting MiC effectively across areas that have restrained built environments but urgently need construction. However, the adoption of MiC varies significantly depending on its intended use. The MiC can be categorized into several main types: temporary structures, residential buildings, educational, commercial, and other buildings (Zhang et al. 2024b). Each type has unique characteristics and requires different policy interventions to promote its adoption effectively. The article focuses on temporary structures and residential buildings, primarily because these areas exhibit widespread demand, mature technology, strong market feasibility, and relatively well-established support systems in terms of policies and regulations. Temporary structures, such as emergency hospitals and quarantine facilities, require rapid deployment and high flexibility (Assaad et al. 2022). Policies promoting these structures focus on expedited permitting processes and emergency funding (Chen et al. 2021; Yatmo et al. 2021). Residential buildings benefit from MiC through faster construction times and reduced labour costs, which prioritize structural integrity, energy efficiency, and aesthetic integration with existing urban landscapes (Pan et al. 2023a; b). Policies for residential MiC often include financial incentives, regulatory support, and public-private partnerships (Akinradewo et al. 2023; Zhang et al. 2023; Zhou et al. 2024). Studies such as Lv et al. (2022) have explored the rapid deployment of MiC in emergency pandemics, highlighting the regulatory adaptations needed to facilitate swift construction responses. Meanwhile, Pan et al. (2023a) focus on the integration of MiC in residential development, emphasizing sustainability and cost-effectiveness over the lifecycle of the building. This study, therefore, provides a nuanced view of how policy can drive MiC adoption effectively across different construction scenarios.

Over the past decade, a growing number of developing economies, such as China, Malaysia, Sri Lanka, and Africa, have sought to identify the most critical enablers or impediments to MiC adoption in their respective countries (Jayawardana et al. 2024; Mao et al. 2015; Nawi et al. 2011). Due to different regulatory environments, market conditions, and cultural factors, the research focus will be skewed in different regions, but in any case, government support and policy factors will be the main driving force for the development of MiC (Jin et al. 2021; Seaden and Manseau 2001). Similar to the UK and Singapore, Hong Kong (HK) has massive construction market growth. Still, it faces various traditional issues of labour intensive, high waste generating, and time-consuming, which was further aggravated by a chronic labour shortage and an ageing workforce (Ekanayake et al. 2021; Pan et al. 2023b). Given its apparent benefits, MiC is deemed a promising contributor to productivity, efficiency, and sustainability by HK policymakers (Choi et al. 2019; Li et al. 2022).

Despite the perceived advantages, the adoption of MiC delivery in HK is nascent (Pan et al. 2023b). Generally, the innovation adoption progress of the HK construction industry is lagging behind advanced countries such as Singapore and Japan (Jin et al. 2022; Xu et al. 2020). Therefore, it is necessary to create a supportive atmosphere for practical implementation to hasten the deployment of MiC. Instead of being considered an alternative technological option at the project planning stage, MiC must be adopted and supported at the industry and policy levels as a viable construction method (Abdul Nabi and El-adaway 2020; Naderpajouh et al. 2016). In this context, HKHA (2019) advocated government financing and additional promotion policies to ignite interest in modular buildings among stakeholders. Researchers have also investigated pertinent concerns (Abdul Nabi and El-adaway 2020). Xu et al.(2020) explored the challenges of implementing modular methods to achieve a higher level of modularisation in dense urban environments. Pan et al. (2023b) developed a scenario for the government-led adoption of MiC. In Singapore, there are numerous policy-supporting frameworks, including the Building Innovation Panel (BIP) and the Buildability Framework, which have facilitated the MiC uptake, thereby promoting productivity and environmental sustainability (Liu et al. 2023). Additionally, Li et al. (2019) pointed out that in Mainland China, policymakers and practitioners can have a more comprehensive understanding of MiC and solve problems more effectively when they encounter difficulties in the process of promotion and application. However, the limited study focused on assessing the Policy-Driving Forces (PDFs) for MiC projects in HK (Jin et al. 2022). Driving forces are all forces that promote change, and these change drivers promote and encourage the change process (Bürgi et al. 2004; Yu and Li 2024). PDFs in MiC refer to the driving forces that promote MiC adoption in terms of public policies.

As a complex system coupling multiple aspects, modelling and assessing the potential impacts of policy factors on the overall uptake of MiC in HK has always been a convoluted issue (Yang et al. 2021; Zhang et al. 2024a). Various scholars have adopted different methods to model policy-related systems. Their results vary widely due to diverse modelling methods and research areas (Li et al. 2023; Pervez et al. 2021; Xu et al. 2020). According to Pan et al. (2023b), the involvement of the government, academia, and all sectors of society has contributed to the successful implementation of MiC in HK. The lack of supporting organisations, such as fabricators and suppliers of prefabricated components, prefabrication contractors, and design consultants, is one of the main issues impeding the growth of MiC, as previously noted in the literature analysis (Abdul Nabi and El-adaway 2020; Assaad et al. 2022). For instance, only skilled module fabricators can create high-quality modules that meet the demands of their customers (Wu et al. 2022). As a result, it is believed that examination preparation for supporting organisations is essential to the success of projects (Zhao et al. 2023). As a key decision maker, the client's readiness to adopt MiC and comprehend its advantages and limitations fluences the market demand considerably (Jiang et al. 2018; Jin et al. 2022). The widespread rollout of MiC necessitates adjustments to the long-established workflow of traditional, site-intensive buildings (Ekanayake et al. 2021). Hence, MiC initiatives cannot succeed without the client's desire to venture outside its comfort zone and without the client's managerial, technical, and financial support (Thompson 2019).

As the largest MiC client and policymaker in HK, the government plays a vital role during its uptake (Hazarika and Zhang 2019). MiC was officially introduced in the *Policy Address 2017* as an initiative, then several key policies have directly influenced the adoption and implementation of MiC. The Buildings Department has introduced specific measures (*Joint Practice Note No. 2* in 2002) to promote prefabrication in construction to address issues such as labour shortages, safety concerns, and environmental impact. Recent policies include *The Technical Circular (Works) No. 2/2020*, implemented in March 2020, which provides guidance on the adoption of MiC for new government buildings and government-funded building projects tendered on or after 1 April 2020. Another critical policy is *PNAP ADV-36*, which aims to provide design requirements, quality control and supervision of MiC, help users share MiC information, and enhance public access to information. These policies form the regulatory backdrop against which our model simulates the impact of PDFs on MiC uptake. As the promotion of MiC encounters policy-related issues that significantly impede the performance of the construction sector, policy-related research is even more crucial for invigorating MiC uptake in HK. In addition, current policies that encourage MiC implementation tend to emphasise incentive programs and legal restrictions (Hsu et al. 2019). These interventions often ignore the dynamic impacts of PDFs on real-world MiC processes, which can have a significant impact on the widespread adoption of MiC (Assaad et al. 2022; Li et al. 2022). The construction practitioners also demand strong patronage from the implementation of extension policies to further promote the realisation of the MiC's widespread adoption. Against this backdrop, a thorough exploration of PDFs in MiC practice is indispensable in HK.

The System Dynamics (SD) method, proposed in the late 1950s by Professor Jay W. Forrester at the Massachusetts Institute of Technology, is a computer-aided approach to strategy and policy design based on feedback systems theory (Forrester 1997). SD is widely applied to dynamic problems arising in public policy, economics, defence, environmental studies, engineering, construction management, theory-building in social science (Leon et al. 2018; Liu et al. 2019; Wang and You 2021). SD modelling can be adopted to investigate the behaviour of complex systems over time with changes of variables (Sterman 2000). In addition, simulation can be used to gain insight into problems to develop strategies and practices that lead to improved system performance. The use of SD in construction management has grown significantly, offering insights into the complex interplay of variables that affect project outcomes (Ding et al. 2016; Jo et al. 2015). Seminal works by Sterman (2000) laid the foundation for using SD to model industrial processes, while recent applications have expanded to address policy impacts in construction (Bakhshayesh and Abbasianjahromi 2023; Jiang et al. 2015). These studies demonstrate the utility of SD in simulating the dynamics of construction projects and the longitudinal effects of policy changes. Shiboub and Assaf (2022) demonstrated how SD modelling can be used to better understand the challenges associated with sustainable road construction and maintenance, and propose policy recommendations to enable these vital activities to be undertaken sustainably. Moreover, in order to explore the effectiveness of the prefabricated building industrial policy, Yildiz et al. (2020) established an SD model of industrial policy for prefabricated buildings in Nanjing.

However, while this approach has been widely adopted to scrutinise the complexity and dynamics of construction projects, there is neither known effort to analyse PDFs in modular buildings employing SD modelling principles, nor adequate efforts to investigate the behaviour of complex systems of MiC uptake over time as variables change (Nasir and Hadikusumo 2019). In light of these nubilous policy-related research and dynamic impacts, further investigation from the HK perspective is needed. While precursor study has provided foundational insights into the critical PDFs affecting MiC adoption in HK, which identified key factors such as regulatory frameworks, promotional initiatives, and sustainability concerns (Jin et al. 2022). However, it primarily offered static analyses that did not account for the complex, dynamic interactions of these factors over time. This study extends the body of knowledge by shifting from a static to a dynamic analysis of how these PDFs interact over time and across different project phases, providing a more comprehensive and actionable framework for promoting MiC in HK. Thus, this paper endeavours to develop an SD model to simulate and evaluate the dynamic impact of critical PDFs, and to reveal improvements to policy-making for overall uptake of MiC.

Following this introduction, the remainder of the paper is presented: Section 2 provides an overview of the research methodology used in this study, including an overview of the SD model development that captures the MiC uptake factors. Section 3 presents the data analysis process and model simulation results. Then, underlying strategies for MiC uptake are discussed in section 4. Finally, section 5 summarises the whole study along with research implications, limitations and future directions.

2. Research Method

A sophisticated design and robust research methodology was required to examine and assess critical PDFs and their potential impact on the overall MiC uptake over time by developing an SD model. **Fig. 1** meticulously depicts the research flow pattern and methods used, along with the research outcomes involved. Accordingly, SD was adopted as the core analytical tool, with well-designed questionnaires and case studies being the main data acquisition techniques.

The SD approach was operationalized through the use of Vensim PLE software, which facilitated the integration of several modeling techniques essential for this analysis. Causal Loop Diagram was first developed to conceptualize and visualize the feedback loops and causal relationships between the various elements influencing MiC adoption. The diagram helped in identifying and mapping the systemic structure and interactions of PDFs (Fig. 3). Stock and Flow Diagram (SFD) was then constructed to translate the conceptual CLD into a quantifiable model that allows for simulation. The SFD incorporates variables and flows that represent the dynamic accumulation and depletion of resources, enabling the simulation of policy impacts over time (Fig. 4). Partial Least Squares-Structural Equation Modeling (PLS-SEM) was utilized to analyze the data gathered from surveys, providing empirical weights to the relationships depicted in the CLD and SFD. This integration ensured that the model simulations were grounded in empirical data, enhancing the validity and applicability of the results.

2.1 Data Collection

Basic research data were collected by questionnaire investigation to get the experts' opinion on the occurrence possibility and impact degree of PDFs (mainly ascertained by systematical literature review) during MiC project phases- initiation, planning and design, and construction, then further analyse the data to obtain critical PDFs and for subsequent model establishment. All questionnaires should initially be tested through a pilot study completed by a small group of sample recipients (Fellows and Liu 2008). Based on the feedback from those respondents, an opportunity was obtained to improve the questionnaire. Five experts with rich experience and vast knowledge of MiC projects were invited for the pilot study, providing a research-oriented view of the questions. Their comments and answers were incorporated into the finalised questionnaire. Then the survey was conducted to solicit the views of MiC professionals. Most of the participants were practitioners working or having vast knowledge and experience in MiC projects in HK, especially governments and contractors were preferred when inviting the respondents. A total of 212 questionnaires were sent via email with online links and face-to-face distribution during this process, while the number of feedback collected was 89, 85 of which were deemed valid and could be used for further analysis. The valid return rate is 40%, which is reasonable, acceptable and higher than the average response rate for an online survey (33%) (Nulty 2008). Besides, 85 responses are higher than those of previous survey-based construction management studies (Adabre and Chan 2019; Ekanayake et al. 2021; Owusu et al. 2020). Indeed, the MiC technology is still in its infancy, and the number of experts who are familiar with and involved in it is not large, which justifies that sample 85 is generally reasonable and reliable to derive meaningful conclusions concerning the MiC policy area. In the effective sample, the background of the respondents is diverse, including government, client, main contractor, manufacturer, transporter, designer, consultant, related researcher, and supplier of materials/equipment. Most of them are directly influenced by the implementation of MiC policies in HK. The preparation of questionnaires, the discussion of the pilot study with all necessary details related to the expert survey, statistical validation using Cronbach's alpha, and the specific process of factor analysis, which were explicated in the precursor study by Jin et al. (2022).

MiC projects are in nature dynamic, including the dynamic movement of modular units and dynamic site conditions (Abdelmageed and Zayed 2020; Xue et al. 2024). The policy impact, however, is not acquired by instantaneous optimisation computations, which has to go through an adaptive adjustment process. Thus, a dynamic model is indispensable in recognising the dynamic impacts of critical PDFs for the overall MiC uptake. With its capability to analyse dynamic interaction mechanisms involved, SD is more appropriate for this study of investigating the cumulative impacts of various PDFs in complex MiC project environments, making this research closer to reality and taking a step forward in instigating appropriate strategies to promote the excellent performance of MiC.

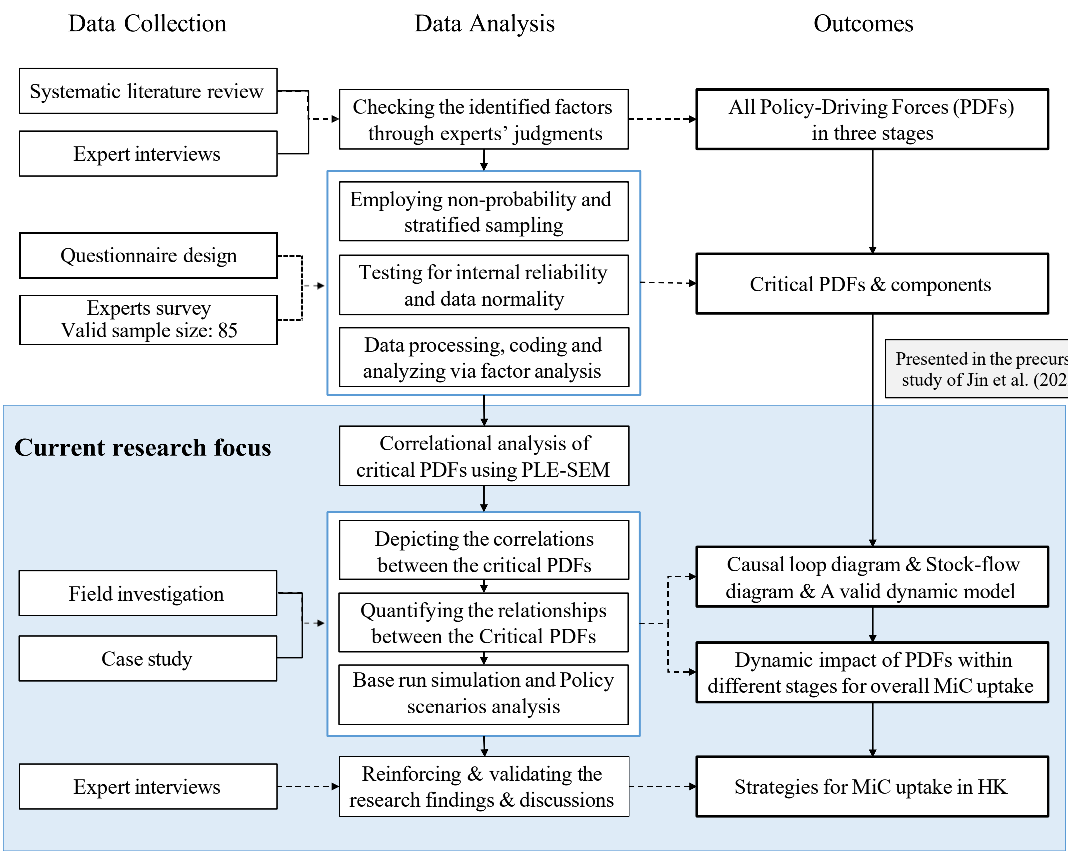

Fig. 1. Research flow and methods used in this study. Source: Authors own work

2.2 Model Establishment

2.2.1 Conceptual model of MiC uptake

The multiple benefits of modular buildings (e.g. cleaner, high quality, circular economy) have led to increased MiC recognition and substantial investment in HK, which includes the initiation of relevant policies and incentives to boost the MiC uptake (Wuni and Shen 2020). This SD model was established to measure the impacts of critical PDFs on the MiC uptake, which mainly involved regulation, promotion, sustainability, Greater Bay Area development, and technology aspects. Existing studies have already shown that relevant PDFs can effectively improve the implementation of MiC policies and ultimately facilitate the achievement of the further large-scale adoption of MiC (Gao and Tian 2020; Mao et al. 2015).

The policy support in the initiation phase (Stage I), planning and design phase (Stage II), and construction phase (Stage III) are conducive to further MiC uptake in HK. Each of these three components is composed of various underlying PDFs, which determine their overall effectiveness. A project usually starts from Stage I, when the client or developer carries out a detailed project feasibility study analysis, to determine whether and to what extent modularisation technology should be adopted. After the decision to adopt MiC, it moves to Stage II, during which the scheme design, finance and construction documents design need to be completed. In HK, the design needs to comply with the Buildings Ordinance and other relevant requirements and procedures to seek statutory approvals. Early engagement of module suppliers and the local contractor is required in some public projects. As the MiC project officially unfolds, all construction activities will be completed in Stage III until the project is successfully delivered. In summary, Stage I is the premise of Stage II and Stage III, and Stage II promotes the completion of Stage III. The smooth progress of the three stages has made corresponding efforts for the further uptake of MiC, namely policy support via the initiation phase, the planning & design phase and the construction phase. **Fig. 2** intuitively displays the interrelationships between these subsystems.

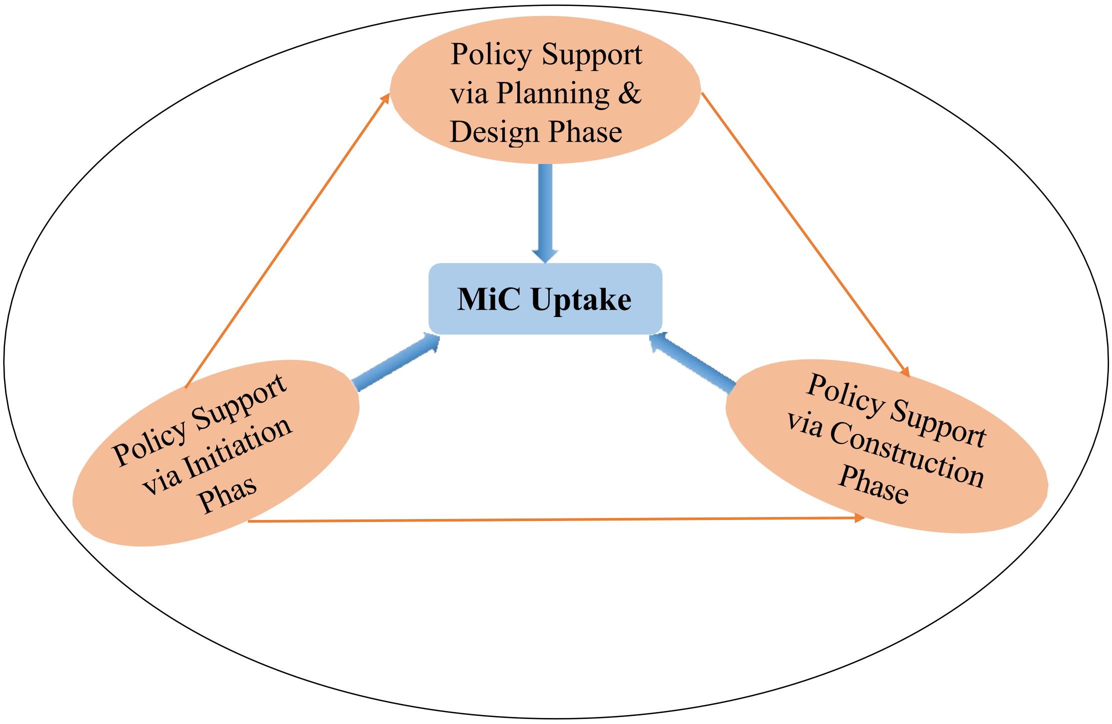

Fig. 2. Theoretical relationships among subsystems. Source: Authors own work

Multiple PDFs are embedded in the different stages of MiC, driving the wide range of its applications. As shown in **Table 1**, critical PDFs have been identified in the precursor study (Jin et al. 2022), with seven, six, and ten in Stages I, II, and III, respectively. These critical PDFs are categorised into regulative, promotional, sustainable, Greater Bay Area development and technical PDF components. Relationships between different variables were measured and modelled using SD in *Vensim PLE* software.

Table 1. Critical PDFs that improve MiC uptake in HK

Stages	Components	Critical PDFs in MiC in HK	Reference
Stage I: Initiation Phase	Component I-1 Promotional & Sustainable PDF **(PSPDF)**	Change of the Government policy related to the preferential interest of the MiC project	(Chen et al., 2017; Lu et al., 2018)
		Change of the Government policy related to taxation and revenue	(Liu et al., 2016)
		Change of the Government policy related to investment of the MiC	(Chiang et al., 2006; Jiang et

		project	al., 2018)
		Change of the Government policy related to environmental protection	(Lehmann, 2011; Lu & Yuan, 2012)
		Change of the Government policy related to the publicity of MiC	(Jiang et al., 2018; Zhang et al., 2017)
	Component I-2 Regulative PDF **(RPDF)**	Change of the Government policy related to COVID-19 pandemic	Interview
		Adjustment of the Government policy related to housing policy	(Huang et al., 2018; Mare, 2018)
Stage II: Planning & Design Phase	Component II-1 Sustainable PDF **(SPDF)**	Change of the Government policy related to construction waste disposal charging scheme	(Ghisellini et al., 2018; Lu & Yuan, 2012)
		Change of the Government policy related to housing policy, the restriction on the type and the size of property development	(Huang et al., 2018; Mare, 2018)
		Change of the Government policy related to environmental protection	(Lehmann, 2011; Lu & Yuan, 2012)
	Component II-2 Regulative PDF **(RPDF)**	Change of the Government policy related to the proportion of prefabrication in public housing projects	(Chiang et al., 2006; Jiang et al., 2018)
		Change of the Government policy related to COVID-19 pandemic	Interview
		Change of the Government policy related to the procurement system	(Guerzoni & Raiteri, 2015)
Stage III: Construction Phase	Component III-1 Greater Bay Area development PDF **(GBADPDF)**	Change of the Government policy related to the customs clearance facilitation in Greater Bay Area, such as facilitating personnel exchange and enhancing the flow of goods	Interview
		Change of the Government policy related to the transportation and logistics in Greater Bay Area, such as expediting cross-boundary infrastructural connectivity	Interview
		Change of the Government policy related to building a globally competitive modern industrial system and jointly cooperation platforms in Greater Bay Area, such as flow of data and information	Interview
	Component III-2 Technical and Regulative PDF **(TRPDF)**	Change of the Government policy related to the authoritatively designed standards, codes and guidelines for MiC	(Han & Wang, 2018; Lu et al., 2018; Mao et al., 2013)
		Change of the Government policy related to scope/type of the prefabricated elements and components	(Chiang et al., 2006; Wuni & Shen, 2020)

	Change of the Government policy related to MiC technological support and innovation	(Han & Wang, 2018; Tykkä et al., 2009)
	Change of the Government policy related to COVID-19 pandemic	Interview
Component III-3 Promotional PDF **(PPDF)**	Change of the Government policy related to finance	(Jiang et al., 2018)
	Change of the Government policy related to the standard of the acceptance of the completed construction quality	(Zhang et al., 2017)
	Change of the Government policy related to the sale of the MiC buildings	Interview

Source(s): Authors' own preliminary work- Jin *et al.* (2022)

2.2.2 Causal loop diagram

A CLD is an intuitional representation that portrays the interconnectedness of various variables and the structure of an SD model (Sterman 2000; Yuan 2012). It can dynamically track the chain effects of the cause through a series of related variables and then trace back to the original cause (LI et al. 2024; Yuan 2012). A CLD consists of nodes and arrows, where nodes represent related defined variables and arrows refer to the cause-and-effect relationships amongst the variables. A positively marked causal link implies that a change in the first variable A causes a change in the other variable B in the same direction (meaning that it increases or decreases at the same time), and the polarity on the arrowheads will be signed (+). In this research, MiC uptake is measured to increase the effectiveness of critical PDF measures. Additionally, variables at three stages were discussed. The main loop includes the positive indicators (+): PDF, which enhances adoption and accumulates the impact of MiC uptake. The positive loops are the three-stage critical PDFs, which can promote the smooth uptake of MiC in HK. **Fig. 3** shows these causal interactions within the CLD to uncover the PDF impacts in MiC.

The variables in each stage are signified by nodes, and links are used to indicate their relative dependencies. Since the critical PDFs are all positively promoting the adoption of MiC, the feedback circles in this study are all positive. This figure aims to depict how the critical PDFs at different stages interact to influence the uptake of MiC in the model.

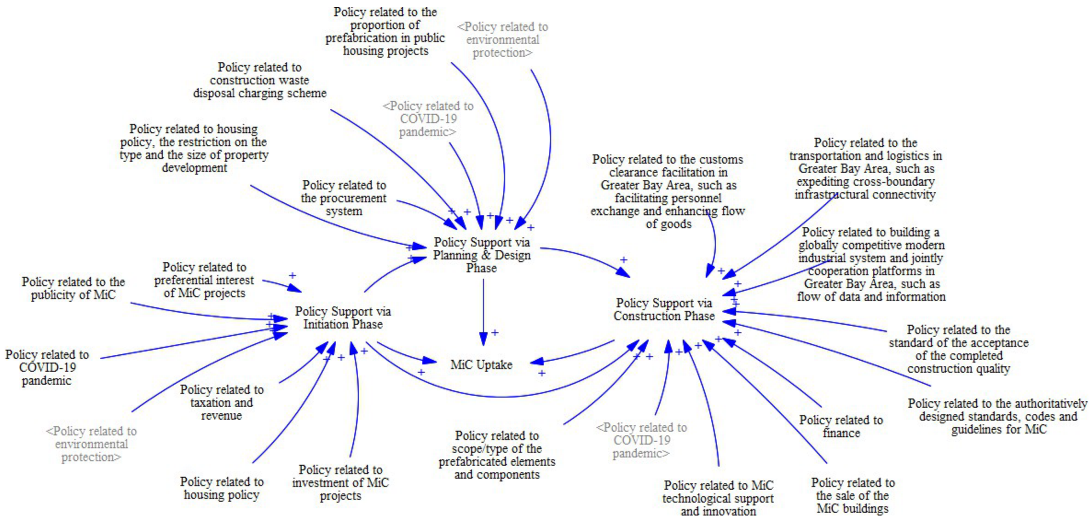

Fig. 3. Causal loop diagram of the PDFs for MiC uptake. Source: Authors own work

2.2.3 Stock-flow diagram

The SFD is another intuitive method to visualise the causal interrelationships between variables and feedback processes in SD modelling (Sterman 2000). Subsequent to determining the relationships between the main variables defined in the CLD, the SFD was performed to quantify their impacts. Unlike CLD, which is limited to assisting problem understanding and displaying causality, the SFD further enhances mathematical simulation and quantitative analysis of the elements in SD models (Wang et al. 2015). With some algebraic expressions written with equations and computer codes, the SFD was developed to simulate the dynamic relationships among various PDFs for MiC uptake. **Fig. 4** presents the SFD of the model, and descriptions of notations are detailed in **Table 2**, including stocks, flows, auxiliary variables, and constant indicators. It provides a boulevard to simulate the influence of a variable on different components of the model and the model as a whole. In this way, the impact of adopting strategies at different stages on the MiC uptake can be simulated.

Table 2. Descriptions of the model variables

Acronym	Variable name	Variable type
CCFiGBA	Change of the Government policy related to the customs clearance facilitation in Greater Bay Area, such as facilitating personnel exchange and enhancing the flow of goods	Constant
CCQ	Change of the Government policy related to the standard of the acceptance of the completed construction quality	Constant
CioCON	Combined impact of Construction Phase	Auxiliary
CioINI	Combined impact of Initiation Phase	Auxiliary
CioP&D	Combined impact of Planning & Design Phase	Auxiliary
COverallIPDFoMiC	Combined Overall impact of PDFs on MiC	Auxiliary
CWDCS	Change of the Government policy related to construction waste disposal charging scheme	Constant
EPI	Change of the Government policy related to environmental protection in Initiation Phase	Constant
EPP	Change of the Government policy related to environmental protection in Planning & Design Phase	Constant
HP	Adjustment of the Government policy related to housing policy	Constant
HP&RPD	Change of the Government policy related to housing policy, the restriction on the type and the size of property development	Constant
IoMiCP	Change of the Government policy related to investment of the MiC project	Constant
IPDFfC	Impact of PDFs on MiC for Construction Phase	Stock
IPDFfI	Impact of PDFs on MiC for Initiation Phase	Stock
IPDFfPD	Impact of PDFs on MiC for Planning & Design Phase	Stock
IS&CPiGBA	Change of the Government policy related to building a globally competitive modern industrial system and jointly	Constant

	cooperation platforms in Greater Bay Area, such as flow of data and information	
OverallIPD FoMiC	Overall impact of PDFs on MiC	Stock
PCPC	Change of the Government policy related to COVID-19 pandemic in Construction Phase	Constant
PCPI	Change of the Government policy related to COVID-19 pandemic in Initiation Phase	Constant
PCPP	Change of the Government policy related to COVID-19 pandemic in Planning & Design Phase	Constant
PI	Change of the Government policy related to the preferential interest of the MiC project	Constant
PoMiC	Change of the Government policy related to the publicity of MiC	Constant
PPPHP	Change of the Government policy related to the proportion of prefabrication in public housing projects	Constant
PrF	Change of the Government policy related to finance	Constant
PS	Change of the Government policy related to the procurement system	Constant
SC&GfMiC	Change of the Government policy related to the authoritatively designed standards, codes and guidelines for MiC	Constant
SoMiC	Change of the Government policy related to the sale of the MiC buildings	Constant
SPC	Change of the Government policy related to scope/type of the prefabricated elements and components	Constant
T&LiGBA	Change of the Government policy related to the transportation and logistics in Greater Bay Area, such as expediting cross-boundary infrastructural connectivity	Constant
T&R	Change of the Government policy related to taxation and revenue	Constant
TSI	Change of the Government policy related to MiC technological support and innovation	Constant
VIPDFfC	Values (adoption level) of IPDFfC	Flow
VIPDFfI	Values (adoption level) of IPDFfI	Flow
VIPDFfPD	Values (adoption level) of IPDFfPD	Flow
VOverallIP DFoMiC	Values (adoption level) of OverallIPDFoMiC	Flow

Source: Authors own work

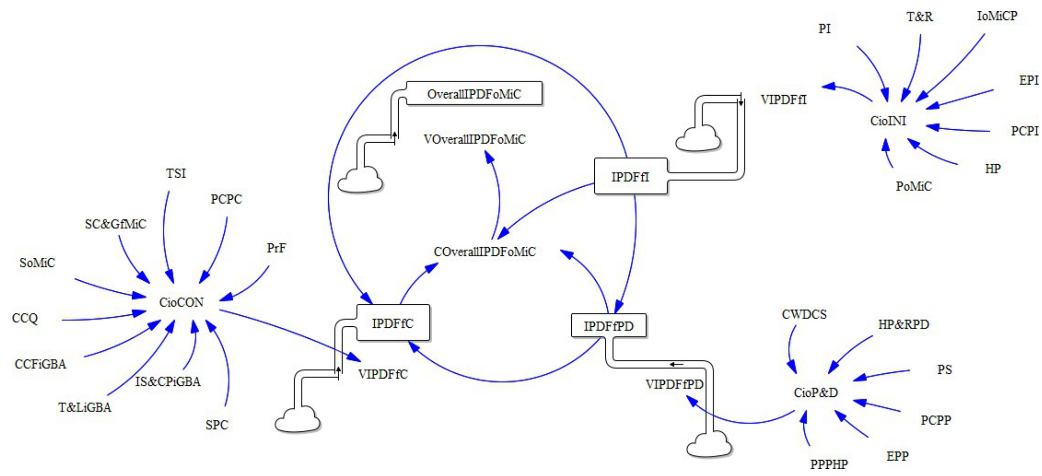

Fig. 4. Stock-flow diagram of the PDFs for MiC uptake. Source: Authors own work

2.3 Model running and testing

To calculate the relative impact value for each PDF, with reference to Ajayi's research (2016), mathematical models for this system were developed for the various potential variables. The main steps involved are explained as follows.

I. Compute the significance index of each primary variable

First, a Partial Least Squares-Structural Equation Modelling (PLS-SEM) model was developed based on the data collected by questionnaire survey, reflecting the correlations between critical PDFs and various phases. The weighting score for each interconnection within the system was calculated from the PLS-SEM model. Specific details of the calculated values are provided in **Appendix I**. Based on these factor weights, the relative weight for each primary variable was calculated using the following Equation 1:

$$R_{!!} = \frac{""_{!}}{\sum_{\$\%\&}^{\#} ""_{!}} \quad (1)$$

where w_{x_i} is the factor weight of x_i derived from the PLS-SEM model, R_{x_i} represents the significance index of the primary variable x_i, implying the contribution of x_i to its latent variable.

For example, a latent factor ‘policy support via Initiation phase’ where x_1=PI, x_2 =T &R, x_3 = IoMiCP, x_4 = EPI, x_5 =PoMiC, x_6 = PCPI, x_7 = HP, and w_{x_1}=0.746, w_{x_2}=0.710, w_{x_3}=0.712, w_{x_4}=0.687, w_{x_5}=0.728, w_{x_6}=0.499, w_{x_7}=0.432. Then, as in Equation 1, the relative weight of PI, $R_{x_1} = \frac{0.746}{4.514} = 0.17$.

II. Compute the impact level of first-order latent variables

Next, the impact levels of first-order latent variables such as ‘policy support via Initiation phase’ were calculated using the following Equation 2:

$$IL(X) = \sum_{i=1}^{n} L_{x_i} \times R_{x_i} \tag{2}$$

where $IL(X)$ denotes the impact level of a latent variable (X), L_{x_i} is the impact level of the primary variable x_i that contributes to the latent variable (X), and R_{x_i} represents the significance index of the primary variable x_i as calculated through Equation 1.

III. Compute the significance index of all latent variables

Thereafter, the significance index of each latent variable was calculated using the following Equation 3, and this step is to understand each phase’s (initiation, planning and design, and construction phase) significance towards promoting the MiC uptake:

$$R_{l_i} = \frac{w_{l_i}}{\sum_{i=1}^{m} w_{l_i}} \tag{3}$$

where w_{l_i} is the absolute weight of latent variable derived from the PLS-SEM model,

$\sum_{31\%}^{0} w2_{!}$ denotes the sum of absolute weights for all latent variables, $R2_{!}$ represents the significance index of latent variable $X_{\$}$, implying the contribution of $X_{\$}$ to the overall MiC uptake.

IV. Compute the combined impacts of Stages I, II, and III

Correspondingly, the impacts of the three stages were calculated through the impact levels as well as the relevant significance index of their contributing factors. This computation was done via Equation 4:

$$CioA = IL(Ini) \times R(Ini) + IL(P\&D) \times R(P\&D) + IL(Con) \times R(Con) \quad (4)$$

where $CioA$ denotes the combined impact of all phases strategies, and relevant IL and R values were calculated using Equation 2 and Equation 3.

All necessarily related values were entered into the model, denoting the unit as 'Dmnl' as the inputs are measured in percentage or scale. Prior to quantitative analysis and simulation, model testing is an indispensable section in SD modelling (Sterman 2000), which is utilised to ensure that the constructed model can well reflect the accuracy of the actual conditions in a reasonable mode (Richardson and Pugh 1981). To build confidence in the model, various structural and behavioural tests were performed to review and confirm the model's validity. The series of tests proposed by Qudrat-Ullah and Seong (2010) includes five aspects: 1) structure verification test, which verifies whether the structure of the established model is logically consistent with the relevant real description knowledge simulated in the system; 2) boundary adequacy test, which confirms whether all the essential structures and concepts are included into the model;

3) parameter verification test, which examines whether the parameter values correspond to the system knowledge numerically and descriptively; 4) dimensional consistency test, which evaluates whether the measurement unit of each equation in the model is in line with the use of parameters; and 5) extreme condition test, which tests whether the model behaves logically when its input is under extreme conditions. These tests are adopted in this study to review and highlight the reliability and robustness of the model.

Test 1 (structure verification test) checks the logic of the model structure, and the verification can be supported by existing literature or actual data (Ding et al., 2016). As shown in **Fig.3** and **Fig. 4**, the relationship structure involved in the CLD and the SFD is matched with existing professional knowledge and practice. Moreover, since the causalities are based on empirical data or determined from the literature, the model is deemed to be a reasonable and realistic reflection of the real world.

Test 2 (boundary adequacy test) focuses on whether all significant variables have been input and computed into the model and are in line with the aim. A field investigation was conducted, and two experts in the construction industry and three scholars in academia were invited to evaluate whether all important elements that constitute the system were considered in this model. The background information of the five experts is shown in **Table 3**. Through a comprehensive review of the SFD, the research ensures that all fundamental variables are considered in the model, along with meeting the research objective.

Test 3 (parameter verification test) verifies whether the parameter settings are suitable for the actual circumstances of practical MiC projects. In this model, the values of parameters are based on factors rigorously confirmed by literature and the experience of professionals in real life. Therefore, the model can pass Test 3 via *Vensim PLE* software because it reflects the real situation of existing MiC practices.

Test 4 (dimensional consistency test) examines the unit consistency of all variables in the model. The modelling tool, *Vensim PLE* software, has a built-in capacity to validate the dimensional consistency of the model. Thus, with the help of the *Vensim PLE*, this test can be automatically executed after the user has determined the units of all variables. Only when Test 4 passes will the model continue to process subsequent simulations.

Test 5 (extreme condition test) inspects the behaviours of the system under extreme conditions (Bala et al. 2016). According to interviews, construction practitioners believed that without any policy support, the adoption rate of MiC is expected to drop to nearly zero, as the construction industry prefers and is more familiar with the traditional mode. In this study, the behaviour of this model under extreme conditions was simulated with 0% and 100% execution of all strategies. As indicated in **Fig. 6**, the results illustrated the effectiveness of this model. When all strategies are adopted at 0%, the overall impact efficiency of critical PDFs on MiC uptake is about 38%; when all strategies are adopted at 100%, the overall impact efficiency of critical PDFs on MiC uptake increases to 99.9%.

With the above analysis, the model has passed all the necessary tests, so its effectiveness has been verified. In addition, the model was applied to real-world case studies and continuously refined based on expert feedback, further ensuring its accuracy and reliability for further base run simulation and sensitivity analysis to derive research results.

Table 3. Backgrounds of the five experts in the field investigation

Experts	Organisation	Working/Research experiences (years)	Education	Current position
1	Research institution	20	Doctoral	Director
2	Research institution	8	Doctoral	Senior manager
3	Research institution	5	Doctoral	Staff
4	Main contractor	25	Master's	Director
5	Consultant	18	Master's	Manager

Source: Authors own work

3. Data Analysis and Simulation Results

3.1 Base run simulation

After the SFD was developed, appropriate MiC projects needed to be carefully selected, accompanied by data collection and case analysis to generate the values of the quantified variable. To achieve this objective and avoid occasionality, two case studies of typical residential projects in HK were selected based on knowledge of the projects' background and in-depth interviews with the main stakeholders involved in these projects. Case A is the *BoxPod* and *OPod* by *James Law Cybertecture architects*, and Case B is the Student Residence at Wong Chuk Hang Site for *the University of Hong Kong*. Both buildings are used to verify the model's accuracy and universality.

Case A, a very representative MiC building in HK, is a proprietary, stackable, fully fitted out, low-cost, micro-living MiC housing module designed to alleviate the affordable housing problems in HK. Constructed out of low cost and readily available reinforced concrete box culvert sections, each *BoxPod* contains living space, a pantry and a toilet for up to four persons to live. *OPod* is constructed out of low cost, and readily available 3.1m diameter concrete water pipe; the design utilises the solid concrete structure to house a micro-living apartment for one/two persons with fully kitted out living, cooking and bathroom spaces inside 165 sq.ft. Case B is one of the pilot MiC projects selected by the HK Development Bureau. It comprises two 17-storey towers of student residences, which is expected to be assembled in 6 types of modules, with a total of 884 modules. Prefabricated polished-flooring, anti-mould emulsion paint walls and ceiling for each room will be completed in the factory. All fixed furniture modules will be installed at the factory in advance. **Table 4** provides further detailed information about these two cases.

Table 4. Detailed characteristics of selected cases

Features	**Project description**	
	Case A	**Case B**
Project type	Newly built public housing	Newly built public housing
Building type	MiC	MiC
Usage	Mirco-living apartment	Student dormitory
Construction commencement date	Jan. 2020	Aug. 2019
Estimated project duration	50 months	65 months
Scope of construction	Over 300 units of fast housing units	Two 17-floor with 1224 hostel places
Location	Tsuen Wan	Police School Road, Wong Chuk Hang

Source: Authors own work

The data was collected through in-depth interviews with several key members within the two case projects. In Case A, the three main members are the director, project assistant manager, and the project architect. Case B involves three key members, including the project manager, the MiC supplier manager, and a sub-contractor representative. From Stage I to II, and then to the official commencement of Stage III, the six participants have comprehensive familiarity or direct participation. They are all experienced and have a deep understanding of MiC with its policies in HK. A survey was intended to determine the extent to which critical PDFs have influenced the project processes of two cases. The involved participants were asked to rate the comprehensive probability impact of each critical PDF in each phase on a scale of 1 to 5, where 1 means slight influence and 5 signifies the impact is great.

The base-run simulation process for each case was initiated following the establishment of the SD model, which included the development of the CLD and the SFD, as well as the completion of basic model testing. To generate the values of the quantified variables required for the simulation, all necessary data were meticulously gathered through unstructured interviews with six project professionals. The specific steps for calculating the relative importance value for each PDF are outlined in Section 2.3. Subsequently, simulations were conducted individually for Case A and Case B using the SyntheSim Simulate functions within the Vensim software. This tool enabled the dynamic analysis of how various PDFs influence the adoption of MiC over time. The results for each case were generated, with the comparison analysis directly outputted by Vensim, providing a clear understanding of the differences between the two cases. The comparison of the base run simulation results is illustrated in **Fig. 5**.

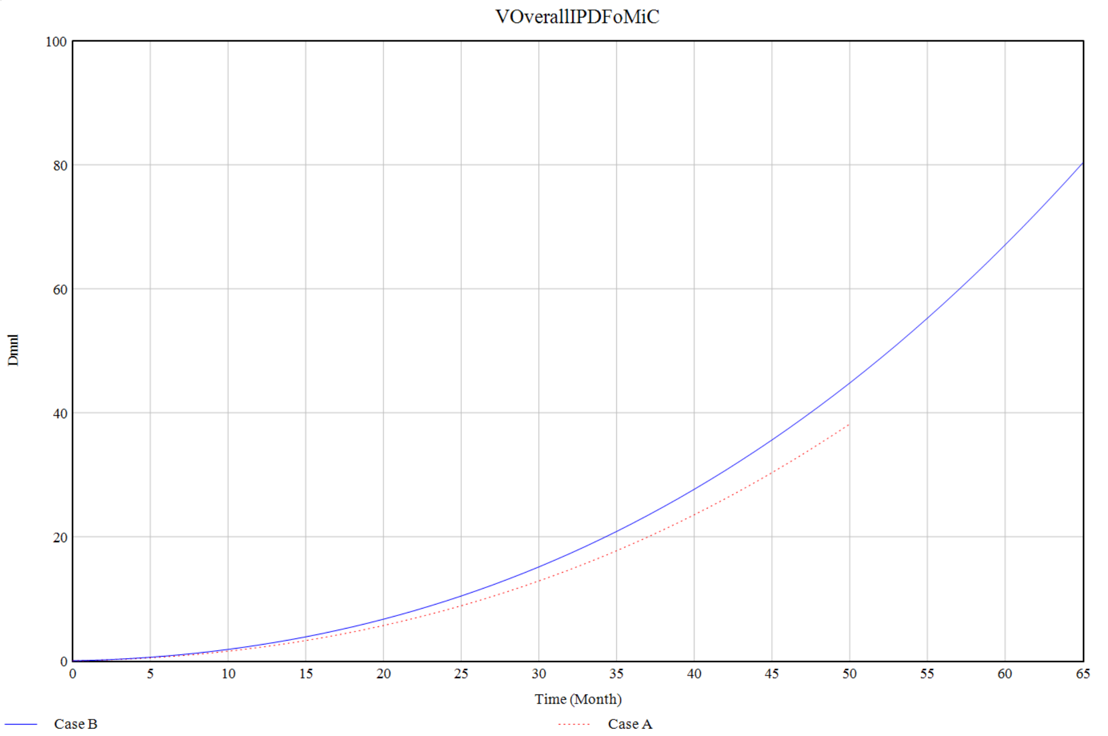

Fig. 5. Base run simulation comparison between Case A & B. Source: Authors own work

In **Fig. 5**, it can be seen that as the project progresses, the value of overall impact of critical PDFs on MiC gradually increases steadily, which shows that all the critical PDFs influence both newly-built public MiC housings, with an impact efficiency of approximately 38% for Case A and about 80% for Case B when projects are delivered successfully. There are reasons behind this significant difference in PDF impact values. These two public housing projects are quite similar, both utilizing MiC technology and having commenced around the same time, meaning the duration of their exposure to policy impacts is the same. The key difference, however, is that the construction scope of Case B is much larger than that of Case A, and the duration of the three phases in Case B is also longer. The results indicate that Case B is more significantly affected by the policies compared to Case A. This suggests that the impact of critical PDFs on large-scale buildings is likely to be more substantial and enduring.

3.2 Policy scenarios analysis

To comprehend the optimal way to increase the uptake of MiC through policy support in HK, various scenarios were modelled and further evaluated in two categories. Scenarios in the first category assessed the impact of each of the three Stages on overall MiC uptake. Scenarios in the second category evaluated the influence of various components and critical PDFs on the overall MiC uptake. During the simulation process, the 50-month duration was chosen based on a combination of real-world case data from Case A, which provided a relevant and practical baseline, and the result of an extreme condition test that demonstrated the system's efficiency stabilized at the 50-month mark. This duration ensures that the simulation accurately reflects the real-world dynamics of MiC adoption and provides a complete picture of the impact of critical PDFs over the project lifecycle.

3.2.1 Dynamic impacts of the three Stages

Scenario modelling was executed using the *Simulate and Synthesim* function within the *Vensim PLE* software to explore the overall influences of each stage. When keeping all other strategies in the case baseline adoption, the corresponding internal implementation level for the individual stage was increased to 100% to assess its overall impact on the MiC uptake. The 'baseline implementation of all current strategies' yielded an adoption efficiency of approximately 38%, and detailed comparison results of scenario modelling are demonstrated in **Fig. 6**. The assumptions and parameter settings underlying **Fig. 6** were carefully chosen to simulate how varying levels of strategy implementation affect MiC adoption efficiency. These settings were informed by expert input and real-world data, ensuring the model reflects the practical dynamics of MiC adoption.

The results reveal that the initiation phase has the most significant impact on the overall MiC uptake. The diagram suggests that at 100% implementation of all critical policies in Stage I, the overall adoption efficiency of MiC would hopefully reach about 80%. It is worth noting that this is not only the result of initiation from a separate perspective, partly because these adjustments can drive implementation and generate positive reactions during the Stage II and III. The construction phase has the second-largest impact on the overall uptake of MiC. The results indicate that the overall adoption efficiency of about 56% for MiC is expected to be achieved when critical policies mentioned in Stage III are at 100% promotion. The increasing adoption of strategies at the planning and design phase can also promote the MiC uptake, although its effect is not as dramatic as in other phases. As shown in **Fig. 6**, the results imply that when the measures at Stage II are 100% implemented, around 50% of the overall MiC adoption efficiency would be achieved, meaning that the policies are effective enough to drive MiC adoption halfway to its maximum potential.

In summary, with the case A baseline adoption efficiency of all current strategies being around 38%, in scenario models, the overall adoption efficiency of MiC can be improved by about 12% in Stage II, while in Stages I and III can be increased by 42%

and 18%, respectively. This further proves that the initiation phase is the most crucial process for MiC uptake, which echoes the insights proposed by Wuni and Shen (2020).

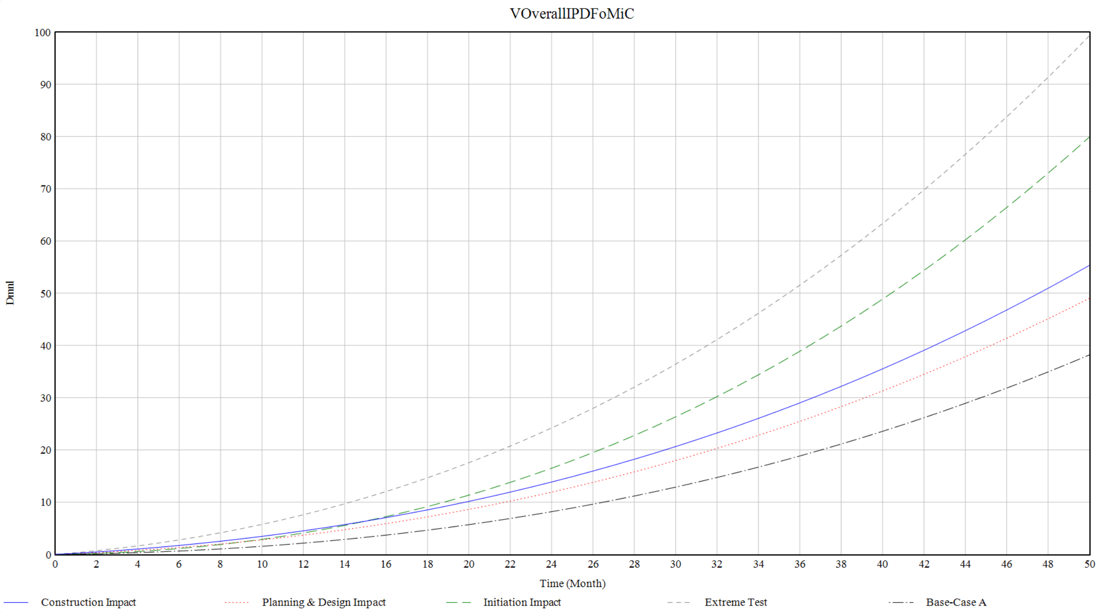

Fig. 6. Dynamic impacts of different stages on MiC uptake. Source: Authors own work

3.2.2 Dynamic impacts of components/critical PDFs

As mentioned in Section 2.3, various scenarios were modeled using the SD approach. By using the *Simulate and Synthesim* function within the *Vensim PLE* software, the impacts of implementing an individual strategy were simulated in a dynamic scenario while keeping all other policies at a baseline, where the effectiveness of each PDF was incrementally adjusted from 0% to 100%. The impact of each PDF was then measured by observing changes in overall MiC adoption efficiency (shown in **Fig. 7**). The outcomes go beyond the single impact of strategy since they reveal the dynamic interaction of critical PDF or related component adopted during different stages.

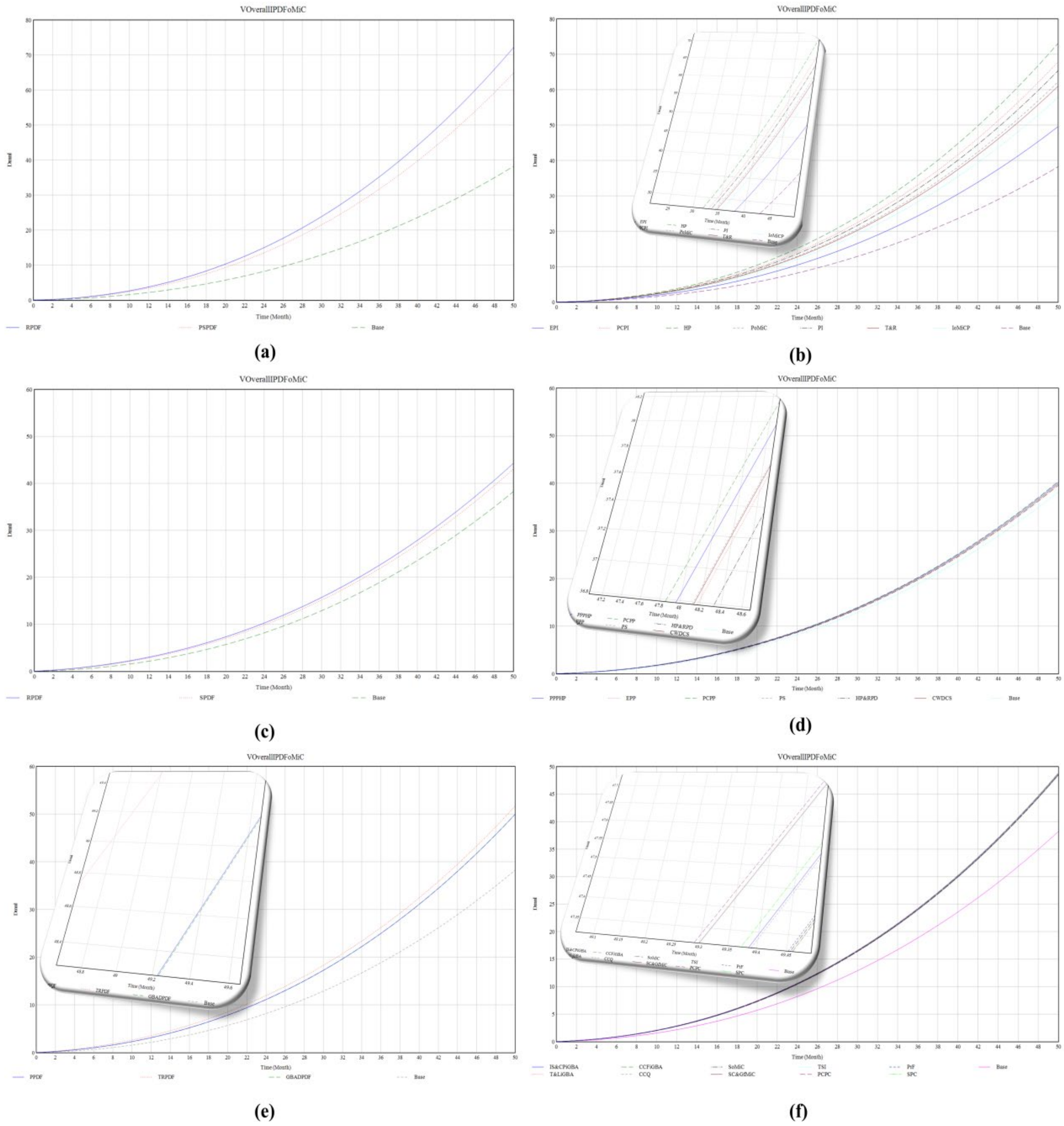

Fig. 7. Dynamic impacts of different components/PDFs on MiC uptake at:

(a,b) Initiation phase; (c,d) Planning & Design phase; (e,f) Construction phase.

Source: Authors own work

Initiation phase

The initiation strategies were simulated to explore how these seven critical PDFs influence the overall adoption efficiency of this modular building method. To comprehensively reflect the effect of different components, the dynamic influence of two components (PSPDF and RPDF) was further simulated and analysed. **Fig. 7(a)** illustrates the simulated varying trends of component I-1 (PSPDF) and I-2 (RPDF), showing that RPDF (with an adoption efficiency of about 72%) has a higher impact on the MiC uptake than PSPDF (65%). This extended dynamic simulation result is consistent with the static factor analysis result in Jin's research (2022). For further detailed analysis on seven separate PDFs, as presented in **Fig. 7(b)**, adjustment of the government policy related to macro housing policy has the highest impact (73%) on the overall MiC uptake. Given that the HK government has provided more public rental housing units and revised the public-private split of new housing supply, coupled with the widespread mandatory adoption of modular construction in public housing, this result makes sense. This is closely followed by the 'COVID-19 pandemic crisis confrontation' (68%), as MiC prides itself on building high-quality and safe-isolation houses within a short schedule (Abdelmageed and Zayed 2020; Luo et al. 2015), the impact of this PDF during the epidemic will be particularly prominent. Other prioritised strategies are the preferential interest of MiC project (65%), the publicity of MiC (62%), taxation reduction (61%), investment in MiC project (58%), environmental protection (50%), based on their significance. These are all policy drivers related to promotion and sustainability, and their influence is slightly lower than regulations.

Planning and design phase

The impacts of different planning and design strategies were simulated to understand the comparison of trends in the influence of six critical PDFs on MiC uptake. There are two components, SPDF and RPDF, each containing three PDFs (in **Table 1**). **Fig. 7(c)** shows the simulated varying tendency of components II-1 (SPDF) and II-2 (RPDF). RPDF (45%) have a greater impact on the MiC uptake than SPDF (43%). Similarly, this dynamic simulation result is consistent with that of Jin's (2022) static factor analysis. The differences are quite subtle when examining the effect of six separate PDFs on overall MiC uptake closely, as illustrated in **Fig. 7(d)**. The 'COVID-19 pandemic crisis confrontation' PDF (41%) has the highest impact during Stage II, while the 'proportion of prefabrication in public housing projects' PDF (40%) takes the second place to exert an influence on MiC uptake. Excellent flexibility in the design phase of MiC is in line with the requirements of the epidemic situation (Tayo et al. 2020; Yatmo et al. 2021). And offsite and modular solutions for the construction industry can respond well to emergencies (Gbadamosi et al. 2020). With the announcement that further MiC applications will raise the utilisation rate of prefabricated concrete components from 70% to approximately 90% on plan (2019), the improvement of MiC housing in HK will be deepened. According to importance, other PDFs include the procurement system, construction waste disposal charging scheme, environmental protection, and micro-housing policy (the restriction on the type and size of property development).

Construction phase

Similarly, the construction strategies were simulated to examine how the effective implementation of these ten critical PDFs individually influences the efficiency of MiC adoption. There are three components in Stage III, GBADPDF, TRPDF and PPDF, containing 3, 4, and 3 different PDFs, respectively (in **Table 1**). **Fig. 7(e)** demonstrates the simulated changing trends of components III-1 (GBADPDF), III-2 (TRPDF) and III-3 (PPDF), and the result revealed that TRPDF (51%) has a more significant impact on the MiC uptake than GBADPDF (50%) and PPDF (50%). It can be clearly observed that the influence curves of GBADPDF and PPDF are very close and almost coincide. However, this result does not correspond to previous Jin's (2022) research, where the GBADPDF was identified as the most influential component. This may be because in factor analysis (a static analysis), on the one hand, there is a slight bias in sample size; on the other hand, most professionals are highly inclined to attach importance to the adjustments related to Greater Bay Area policies, as they significantly affect the efficient transportation of modules in MiC and timely communication between stakeholders (Li et al. 2016; Luo et al. 2019). Also, some practitioners neglected to assess the long-term dynamic impacts of factors from a holistic perspective. In this SD model, technological and regulative policies occupy the dominant role. Technological innovation and progress have always been emphasised by scholars and construction practitioners (Ahmad et al. 1995; Arayici et al. 2011).

Moreover, the impact efficiency of regulative PDFs has been the highest all the time, from Stage I to III. Among individual strategies, as depicted in **Fig. 7(f)**, the policy-related 'COVID-19 pandemic crisis confrontation' (48%) has the most remarkable tendency to improve the overall MiC uptake. The authoritatively designed standards, codes and guidelines for MiC have the second-highest possibility for its uptake, and the influence of technological support and innovation ranks third. The 'COVID-19 pandemic crisis confrontation' policy requires temporary isolation buildings to be completed rapidly and with high quality (WHO 2021), and MiC is the best option (Yatmo et al. 2021). Numerous studies have shown that inappropriate or even absence of design codes and standards for prefabricated components is a critical political factor related to inefficient adoption and poor performance of MiC (Han and Wang 2018; Zhang et al. 2014), so its improvement can well promote the overall MiC uptake in HK. Technological innovation and production would bring about the supremacy of modernism in architecture (Lobsinger 2011). Many researchers attempted to integrate technology into business processes of MiC from the perspective of technological innovation, such as VP-based IKEA model (Li et al. 2011), Internet of Things-enabled BIM platform (IBIMP) for MiC projects (Zhai et al. 2019), and real-time information sharing to support the adoption of offsite technology (Pan et al. 2012). All of these have been verified through practice or case studies to promote MiC uptake.

To fathom top strategies for improving the MiC uptake, the scenario simulation results of different components for three-stage strategies are combined. **Fig. 8** shows varying curves of dynamic impacts of all seven components on MiC uptake along with the order of importance. The result implies that RPDF has the highest tendency to enhance the MiC uptake. Remarkably, the influence of RPDF is always the strongest at each phase. PPDF also attracts attention, second only to RPDF. Other strategies are SPDF, TPDF, and GBADPDF.

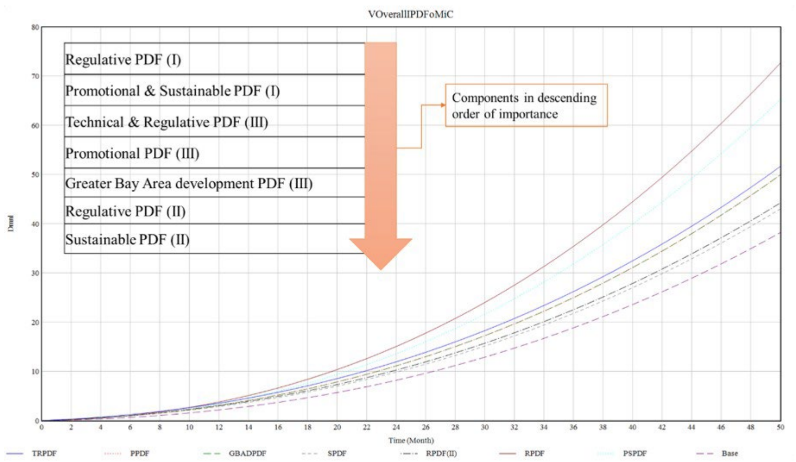

Fig. 8. Dynamic impacts of different components on MiC uptake. Source: Authors own work

The findings indicate that Regulative PDFs have the most significant impact on the adoption of MiC in HK, particularly during the initiation phase of construction projects. This aligns with findings from Khan et al. (2024), who observed the regulatory category as a crucial factor to promote MiC in the Australian context, where regulatory incentives significantly influenced the adoption of green building practices (Navaratnam et al. 2022). Surprisingly, practitioners in Sri Lanka do not consider government regulations to be a significant barrier to the adoption of MiC (Jayawardana et al. 2024). This could be due to the fact that the national context of Sri Lanka is entirely different from that of HK, and the practitioners' optimistic attitude towards proactively improving the prevalence of prefabricated modules in construction projects also varies. Contrastingly, while the simulation highlights the substantial impact of technological support PDFs, Akinradewo et. al (2023) found that in Nigeria, technological advancements were less influential than financial incentives. This discrepancy may be due to differences in market maturity and government policy frameworks between HK and Nigeria. Furthermore, results underscore the importance of governmental policy interventions in promoting MiC, a finding that is corroborated by Shin et al. (2022) in their study of South Korea's construction sector. However, this study extends the understanding by quantitatively modeling the dynamic interactions of these policies over time, providing a unique contribution to the literature on system dynamics in construction management.

4. Underlying strategies for MiC uptake in HK

Based on the results of case simulations and the above-mentioned policy scenarios analysis, Regulative PDF has the highest tendency to enhance MiC uptake in each phase. Particularly, PDFs related to the COVID-19 pandemic crisis confrontation, macro housing policy, the preferential interest of MiC project, MiC technological support and innovation, authoritatively designed standards, codes and guidelines for MiC and GBA development policies have higher significance in promoting MiC uptake compared with other PDFs. Moreover, by further incorporating expert opinions derived from interviews, this study provides the following strategies to enhance the uptake of MiC practices in HK. Each strategy is directly supported by specific findings from SD model simulations.

4.1 Boost MiC adoption in buildings under emergencies

From scenario analysis (Fig. 7), the policy to deal with the COVID-19 pandemic crisis shows its highest impact on the MiC uptake during all three phases. The results indicate that policies related to emergency responses, such as the COVID-19 pandemic, have a profound impact on MiC uptake. The simulations show a significant increase in MiC adoption when emergency-related policies are activated. The significant benefits of MiC lie in its rapid construction speed and controllable high quality (Gao and Tian 2020; Jiang et al. 2018), which significantly contributes to the creation of isolation space for patients during the COVID-19 epidemic and the need for temporary hospitals. Standard quarantine space creation measures used to contain the COVID-19 epidemic include temporary mobile cabins, temporary tent-based structures, newly constructed temporary hospitals, and retrofitted buildings for an emergency, all of which are offsite and modular solutions (Gbadamosi et al. 2020). Emergency engineering projects such as Lei Yue Mun quarantine camp in HK, Huoshenshan and Thunder God Mountain Hospital in Wuhan, are good MiC practices. This motivates the government and construction industry practitioners to respond to emergencies by means of boosting the adoption of MiC in temporary buildings, which can not only promote the overall MiC uptake but also effectively meet the demands of temporary constructions, making it possible for temporary buildings to have better performance. Develop and implement a set of predefined MiC protocols for rapid deployment in emergency scenarios, such as pandemics or natural disasters. These protocols should include streamlined permitting processes and guidelines for emergency construction, potentially increasing MiC's responsiveness and utility in critical times. Implement policy measures like expedited permitting and increased funding for MiC projects that can be mobilized quickly in response to emergencies, as seen during the COVID-19 pandemic. In addition, the detachability of MiC buildings is further conducive to sustainable recycling development, reducing consumables and construction waste.

4.2 Expand MiC adoption in public housing and encourage its application in private buildings

As demonstrated in the initiation phase analysis (Section 3.2.2), macro housing policies heavily influence MiC adoption. The model predicts an enhanced uptake when MiC is integrated into public housing projects. The HK government has promulgated the Long Term Housing Strategy (LTHS), which listed the provision of more public rental housing (PRH) units and subsidised sale flats (SSTs) and the stabilisation of the residential property market as three major strategic directions (Legislative Council of Hong Kong 2021; Transport and Housing Bureau in Hong Kong 2020). Additionally, in 2019, the Legislative Council Panel on Housing adjusted the public-private allocation of new housing supply over the 10 years from 60:40 in 2019-20 to 70:30 in 2028-29. These macro housing policies will have an impact on MiC adoption since prefabricated components are mandatory in public housing. To achieve the housing policy requirements mentioned above, it is highly recommended to leverage government housing initiatives to incorporate MiC more extensively in public housing projects, rather than just prefabricated components because of its unique advantages in accelerating the construction cycle (Chen et al. 2017; Xie et al. 2020). Simultaneously, in interviews with industry practitioners, experts also emphasized the importance of incentivizing private developers to adopt MiC through fiscal benefits or expedited approval processes. This approach could encourage the construction of aesthetically appealing and diverse housing options. Additionally, advocating for policies that mandate or incentivize MiC in public housing projects, along with offering tax incentives or subsidies to private developers, could further broaden its application across the housing sector.

4.3 Provide additional Gross Floor Area (GFA) exemption for MiC projects

The HK Buildings Department has launched a series of preferential interest incentive policies to promote prefabricated development. Regulatory factors, particularly those concerning construction policies, such as the introduction of GFA compensation in 2002 as the most attractive to real estate companies (Zhou et al. 2019), have been identified as significant enablers of MiC adoption (Fig. 8). Adjustments in these regulations can create a more favourable environment for MiC. Similar to incentives provided in Singapore to encourage sustainable building practices, increasing the GFA exemption for projects using MiC could make this construction method more financially attractive. More than a few professionals mentioned that increasing the GFA relaxation percentage for MiC development could remarkably promote the uptake of MiC in HK, as the exemption percentage of GFA has not been adjusted for nearly 20 years. The most effective way to enhance the enthusiasm of real estate enterprises to implement MiC is to strengthen government financial incentives (Jiang et al. 2018), which interviewees have unanimously agreed on in this study. This policy adjustment is expected to stimulate greater interest and investment in MiC projects from the development community.

4.4 Enhance information technology support across the supply chain

The core of improving the construction industry's productivity lies in technological innovations (Slaughter 2000). Findings from the construction phase analysis (Fig. 7e) underscore the importance of technological support in enhancing MiC efficiency and adoption. Effective information sharing and project management facilitated by advanced technology are critical. The effectiveness of promoting the MiC adoption largely depends on solving technical issues; therefore, the government has always attached great importance to promoting the implementation of innovative building technologies (Zhou et al. 2021). Investing in and deploying robust IT systems is essential for enhancing connectivity and integration across the MiC supply chain. The adoption of emerging technologies such as Radio-frequency identification (RFID)/ Near Field Communication (NFC)/ Quick Response (QR) codes can streamline services and tools for stakeholders involved in Stage III, improving daily operations and decision-making across MiC housing project management to ensure timely project delivery (Li et al. 2017). Additionally, advocating for government-backed initiatives to fund the development and integration of these IT solutions will further enhance coordination and efficiency throughout the supply chain. This viewpoint was also supported by project managers and professionals who participated in this study. They explained that these information tracking technologies and communication platforms could well assist timely information sharing throughout the supply chain, and facilitate the orderly installation of modules, contributing to the smooth progress of the overall MiC project schedule. Moreover, efficient supervision systems can be vigorously promoted to effectively record all processes of modules and improve punctuality and productivity by maintaining better control over construction quality, thereby contributing to improved performance and further adoption of MiC. It is believed that with the technological advancement supported by policies, MiC will have a promising prospect.

4.5 Formulate explicit standards and guidelines for MiC

Clear and authoritative guidelines are necessary to standardize MiC practices and boost stakeholder confidence. To date, there are still no authoritative and mature standards and specifications that can guide practitioners to become proficient in using the modular construction approach (Xu et al. 2020). The absence of explicit standards and guidelines has been pinpointed as a barrier to MiC adoption (Section 3.2.2). ‘Inappropriate design codes and standards in modular buildings’ was also listed by Luo et al. (2015) as a top risk factor affecting practitioners’ attitudes toward its implementation. In practice, many practitioners also expressed their opinions in this regard during the interview; that is, standards and procedures of MiC projects urgently need clear rules and regulations to provide guidance, among which the review of statutory submissions related to MiC is also mentioned. In this regard, HK should actively learn from Singapore, which has established a relatively comprehensive policy system to promote the adoption of MiC (Xu et al. 2020). In addition, while requiring buildings to use prefabricated components to achieve buildability, Singapore has closely integrated this requirement with its promulgated series of policies, standards and regulations (Chiang et al. 2006; Mao et al. 2018). Collaboration with industry experts and international bodies is essential to develop comprehensive standards and guidelines for MiC. These standards should encompass design, manufacturing, assembly, and quality assurance to ensure consistency and quality across MiC projects. Engaging with regulatory bodies to create clear and comprehensive guidelines, informed by international best practices, will further enhance the effective implementation of MiC.

4.6 Promote further implementation of relevant policies in the Great Bay Area

The scenario analysis related to the GBA development policies (**Fig. 7e**) illustrates their significant potential to facilitate MiC uptake by improving cross-border operational efficiency. The complex cross-border transportation process is a unique feature that distinguishes HK's MiC approach from other places. Land resources available in HK are limited. The suppliers have established manufacturing plants within the Great Bay Area (GBA) for its economical due to the lower cost of labour and land (Luo et al. 2019). From factor analysis (Jin et al. 2022), the relevant GBA policies are of great significance to the uptake of MiC, while their influence is not so obvious in this SD model. Comprehensive analysis of reasons: First, due to the difference in sample size, this SD model was established based on existing project data, while the previous factor analysis was to integrate the insights of experts and scholars in a large scope; Second, the model is based on the status quo and simulates long-term dynamic impacts, while the large-scale questionnaire survey represents a short-term reflection. It can also be seen that, at the present stage, the relevant GBA policies have not been fully put into practice, leading to a lack of in-depth perception by many practitioners. However, in reality, from the perspective of long-term development, due to the close correlation of the entire GBA in terms of politics geography and economy, they will have a great impact on the MiC uptake in HK. Therefore, the government should strive to enhance and harmonize MiC-related policies across the GBA to streamline the transportation and approval processes for MiC components. This requires close cooperation between HK and Mainland China authorities to ensure seamless logistic and regulatory frameworks. Promoting policies that improve coordination within the GBA will facilitate smoother cross-border operations for MiC projects.

These strategies are formulated based on a rigorous analysis of the dynamic impacts of various PDFs on MiC adoption in HK. Implementing these recommendations requires concerted efforts from policymakers, industry stakeholders, and the community to fully realize the benefits of MiC in enhancing construction productivity, efficiency, and sustainability.

5. Conclusions

This research describes a step-by-step process in the development of an SD model to simulate the dynamic impacts of the initiation, planning and design and construction phases, as well as their associated PDFs, on the overall MiC uptake in HK. The SD model focuses on both specific case projects and general industry trends. The model incorporates real-world data from several high-profile MiC projects currently underway in HK, as well as industry-wide surveys on adoption rates and barriers. The model was established with the help of *Vensim PLE* software, including a CLD and an SFD, in which the latter is converted from the former by means of mathematical equations. Five model tests and validation were conducted to ensure that the constructed model can substantially reflect the accuracy of actual conditions in a reasonable mode. Two case studies of MiC buildings under construction in HK are applied to perform base run simulation, from which the newly built public MiC housings can be concluded to be influenced by all critical PDFs. Various scenarios are simulated to evaluate the impact of each PDF on the overall MiC uptake, including variations in policy support, economic incentives, and technological advancements under different regulatory conditions. The results imply that PDFs in the initiation phase have the greatest impact on the overall uptake of MiC in HK, followed by the construction phase, the planning and design phase. The impact of all critical PDFs during the three stages is evaluated separately. The analysis suggests that Regulative PDF has the highest tendency to enhance MiC uptake in each phase. PDFs related to the COVID-19 pandemic crisis confrontation, macro housing policy, the preferential interest of MiC project, MiC technological support and innovation, authoritatively designed standards, codes and guidelines for MiC and GBA development policies have higher significance in promoting MiC uptake compared with other PDFs. In response to the preceding points, and based on the outcomes of case simulation combined with expert opinions from interviews, this study proposes six specific recommendations for improving MiC uptake: (1) boost MiC adoption in buildings under emergencies (e.g. COVID-19 pandemic), (2) expand MiC adoption in public housing and encourage its application in private buildings, (3) provide additional GFA exemption for MiC projects, (4) enhance information technology support across the supply chain, (5) formulate explicit standards and guidelines for MiC and (6) promote further implementation of relevant policies in the Greater Bay Area.

Theoretically, this study contributes to the body of knowledge by providing a quantitative assessment of PDFs on MiC adoption using an SD approach. This novel application in HK's construction industry offers a dynamic perspective on policy impacts. Also, the findings of this study have significant economic and commercial implications for the construction industry. By understanding the most impactful PDFs, construction companies and developers can optimize their strategies for MiC adoption, potentially reducing costs and increasing efficiency. Practical recommendations include leveraging government housing initiatives, enhancing IT support across the supply chain, and providing additional GFA exemptions for MiC projects. The identified influence of specific PDFs on MiC adoption provides a data-driven basis for drafting and revising regulations and incentives. Moreover, policymakers can use these insights to formulate targeted strategies that enhance the construction sector’s efficiency and sustainability, particularly in urban settings like HK. Recommendations include developing emergency response protocols, providing fiscal incentives for private developers, and enhancing coordination within the GBA. These strategies can inform legislative changes to create a more supportive regulatory environment for MiC. Additionally, the faster completion rates of MiC projects can alleviate housing shortages, improving quality of life and housing affordability in densely populated areas. Therefore, increased MiC adoption can significantly improve housing availability and quality, particularly in emergencies. By promoting MiC, public perceptions of modular construction can shift, highlighting its benefits in terms of sustainability and efficiency. This can lead to broader acceptance and support for MiC projects, ultimately enhancing the quality of life for residents. These implications ensure this research not only contributes to academic knowledge but also provides practical tools and insights that can be directly applied by stakeholders to drive positive change in the construction industry and beyond.

However, some perceptible limitations of this research should be noted to promote the further development and wide application of MiC. Firstly, collecting additional empirical data can further enhance the interpretation and reliability of conclusions, as well as strengthen justifications for model verification in this study. Secondly, the scope of this study is limited in terms of regions; therefore, the results would not necessarily be generalised for all other country contexts. Further, these policy drivers and implications are jurisdiction-specific, their levels of criticality would necessarily differ, but some interesting core commonalities may emerge. Future research could explore the long-term effects of specific policies or compare MiC adoption across different regions to validate and extend these findings. Thirdly, one source of weakness of this study that could have affected the measurements of PDFs is that data collection was performed during the COVID-19 pandemic. Additionally, the policy environment is changeable, indicating that the developed SD model should be improved through periodic review and monitoring of its dynamics to make appropriate adjustments in different periods. Therefore, similar SD modelling can be performed to determine the impact of policy-driving forces on MiC in HK after the COVID-19 pandemic (normal customs clearance and exchanges between HK and the Mainland). Note that the uptake of MiC may be correspondingly enhanced with improved conditions.

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